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Revision 2

Conceptual Framework and Numerical Implementation of 100 Areas Groundwater Flow and Transport Model

Prepared for the U.S. Department of Energy
Assistant Secretary for Environmental Management

Contractor for the U.S. Department of Energy
under Contract DE-AC06-08RL14788

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Program/Project: S&GRP

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APPROVED
By G.E. Bratton at 2:58 pm, Mar 14, 2012

Release Approval

Date

Executive Summary

This model documentation report presents data, analyses and interpretations that are used to construct the conceptual model for unsaturated and saturated zone conditions within the Hanford 100 Areas (Figure ES-1). This report also documents the development of the 100 Areas Groundwater Model (100AGWM), a groundwater flow and contaminant fate-and-transport simulation model developed in support of remedial activities led by CH2M Hill Plateau Remediation Company (CHPRC) at the Hanford Site, Washington. The objective of this report is to concisely describe the conceptual model framework for the 100 Areas; the 100AGWM modeling objectives; the model construction, calibration, validation, deployment and configuration control; and to summarize the assumptions and limitations of the 100AGWM.

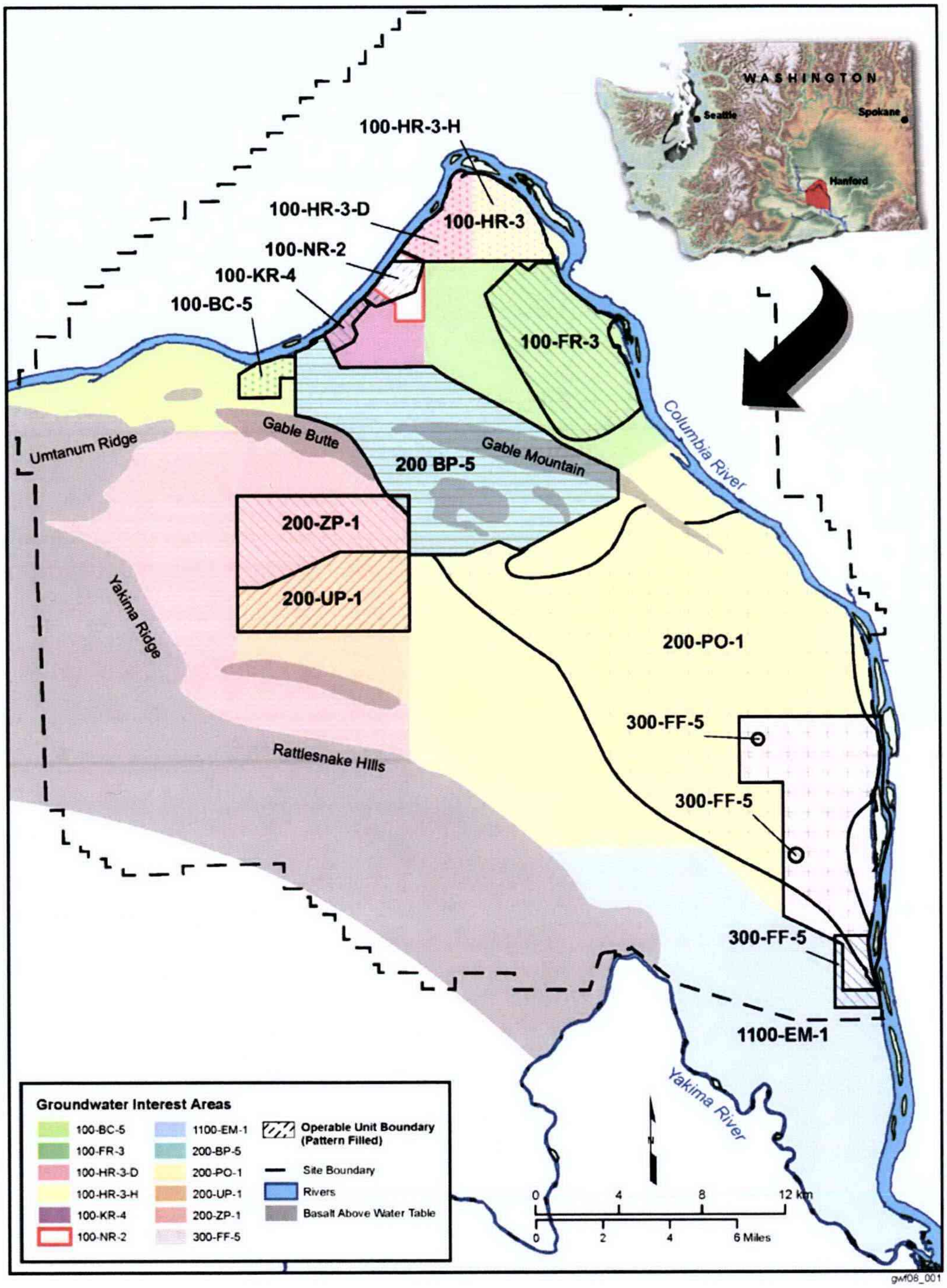
The 100 Area groundwater operable units (OUs) (Figure ES-1) are located adjacent to the Columbia River in the northeastern corner of the Hanford Site. The 100 Area groundwater OUs encompass the operating areas of the former plutonium-production reactors at the Hanford Site. The nine reactors (B, C, D, DR, F, H, KE, KW, and N Reactors) were built from 1943 through 1965. The groundwater OUs are referred as OUs in this report. While the reactors were operational, large volumes of Columbia River water were treated with sodium dichromate (to inhibit corrosion of the reactor piping) and used as coolant for the reactors. In addition, numerous leaks and spills of concentrated sodium-dichromate stock solution occurred over the lifetime of reactor operations, locally introducing much higher concentrations of chromium contamination into the vadose zone and groundwater. While hexavalent chromium is the primary contaminant of concern for 100-FR-3, 100-HR-3, 100-KR-4 and 100-BC-5 OUs (Figure ES-1), migration of other contaminants of concern are examined, including Tritium, Strontium-90, Carbon-14, Nitrate and TCE.

The purpose of the 100AGWM is to provide the computational framework for groundwater flow and contaminant transport modeling for remedial process optimization, the *Hanford Federal Facility Agreement and Consent Order* (Tri-Party Agreement),[1] performance-based incentives and the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) Remedial Investigation (RI) and

1 Ecology, EPA, and DOE, 1989, *Hanford Federal Facility Agreement and Consent Order*, 2 vols., as amended, Washington State Department of Ecology, U.S. Environmental Protection Agency, and U.S. Department of Energy, Olympia, Washington.

Feasibility Study (FS) for the 100 Area Operable Units (OU) of the Hanford Site. The RI/FS will support final remedy selection and provide the basis for a final Record of Decision (ROD) for each OU. Intended and anticipated uses of the model include:

- Calculating groundwater levels, hydraulic gradients, and groundwater flows throughout the model domain, for use in subsequent calculations of the fate and transport of contaminants of concern.
- Estimating future groundwater concentrations of contaminants of concern to support the design and evaluation of remedial alternatives.
- Evaluating selected remedial alternatives, and optimizing final remedial designs in order to achieve specified remedial action objectives.



Source: DOE/RL-2008-66, *Hanford Site Groundwater Monitoring for Fiscal Year 2008.*

Figure ES-1. Location of 100 Area Groundwater Operable Units in Relation to Other Hanford Site Groundwater Operable Units

This report describes the 100 Areas conceptual model framework in terms of the features (e.g., geo-hydrologic information including hydrostratigraphic contacts), events (e.g., natural and anthropogenic recharge), and processes (e.g., river/aquifer interaction and impact of ongoing pump-and-treat remedial actions) that prevail and are of particular import to the various 100 Area OUs. First, background information on the history of the facilities is presented – with an emphasis on disposal operations, process histories, contaminant sources, and the nature and extent of contamination across all 100 Area OUs.

Following this, available site characterization data are summarized and used to sequentially describe and illustrate the dominant features events and processes – focusing particular attention on the hydrogeology of each OU; sources, patterns and rates of recharge; and the groundwater response to the both the adjacent Columbia River and to the currently-operating pump-and-treat remedies. Structural (surface elevation) maps and representative hydrogeologic cross-sections are presented to illustrate the geologic extent and aquifer conditions related to the Hanford/Ringold Formation contact and the Ringold Formation Upper Mud unit (RUM); important features affecting unsaturated flow and transport for the 100 Areas, as well as available information on hydraulic properties for 100 Areas sediments, are summarized; and aquifer properties derived from slug tests and pumping tests for the Hanford and Ringold units are tabulated.

Next, historical hexavalent chromium plume maps are presented to illustrate the approximate extent of contamination by this particular COC within each of the OUs, and to depict the impact of interim pump-and-treat (P&T) remedial actions at the 100-D, 100-H, and 100-K Areas. Discussion of the data and information used to construct the site conceptual model concludes with a presentation of the information available on the flow and transport properties of the unsaturated and saturated zones.

Subsequent sections of the report detail the numerical implementation of these features, events and processes as the 100AGWM – including the software employed, spatial and temporal discretization, aquifer properties, boundary conditions and recharge, and methods used to simulate pumping at wells; model calibration and validation; and the methods used to complete simulations of contaminant transport. Assumptions and limitations that underlie the 100AGWM development and deployment are then summarized.

The 100AGWM represents the most recent incarnation of a model development process that commenced in fiscal year 2008 (FY08) in support of remedy evaluation and remedial process optimization (RPO) activities at 100-K and 100-D. The model version history - summarized in this report - documents the major stages in the development of the 100AGWM. During 2009 an external technical peer review was convened by CHPRC to assess the status of groundwater model development and implementation in support of remedial process optimization activities at the 100-HR-3 and 100-KR-4 OUs. That panel completed a detailed review of the 100 Areas groundwater model as it existed at that time, and provided recommendations for development to enhance the capabilities of the model. At the time of preparation of this model documentation report, the majority of the peer review team recommendations have been implemented during a sequence of revisions and updates that are summarized in the model version history. In keeping with the peer review panel report, this model documentation report concludes by providing recommendations for improvements in either the site conceptual model, or numerical model implementation, to further enhance the capabilities of the 100AGWM.

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Terms

AWQC	ambient water quality criteria
bgs	below ground surface
CERCLA	*Comprehensive Environmental Response, Compensation, and Liability Act of 1980*
CHPRC	CH2M HILL Plateau Remediation Company
COC	contaminant of concern
DOE	U.S. Department of Energy
DWS	drinking water standard
Ecology	Washington State Department of Ecology
EMMA	Environmental Model Management Archive
EPA	U.S. Environmental Protection Agency
FY	fiscal year
GIS	geographic information system
gpm	gallons per minute
ISRM	In Situ Redox Manipulation
Kd	distribution coefficient
LWDF	liquid waste disposal facility
NAVD88	North American Vertical Datum of 1988
OU	operable unit
PNNL	Pacific Northwest National Laboratory
ppm	parts per million
RCRA	*Resource Conservation and Recovery Act of 1976*
RI/FS	remedial investigation/feasibility study
RL	U.S. Department of Energy, Richland Operations Office
RPO	remedial process optimization
RUM	Ringold Upper Mud (unit)
Tri-Party Agreement	*Hanford Federal Facility Agreement and Consent Order*
USGS	U.S. Geological Survey

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1 Introduction

The 100 Area groundwater operable units (OUs), are located adjacent to the Columbia River in the northeastern corner of the Hanford Site in southeastern Washington State (Figure 1-1). The 100 Area OUs encompass the operating areas of the nine former plutonium production reactors (B, C, D, DR, F, H, KE, KW, and N Reactors), which were built from 1943 through 1965. While most of the reactors were single-pass reactors that operated only for plutonium production, the N Reactor was a dual-purpose reactor operated for plutonium production as well as electricity generation. As a legacy of the operation of these reactors, and related activities, the subsurface in the 100 Areas is impacted by a variety of contaminants.

While the reactors were operational, large volumes of water pumped from the Columbia River were treated with sodium dichromate (to inhibit corrosion of the reactor piping) and used as coolant for the reactors. Leaks and spills of concentrated sodium-dichromate stock solution occurred over the lifetime of reactor operations, locally introducing high concentrations of chromium contamination into the vadose zone and groundwater. As a result, hexavalent chromium is the principal contaminant of concern (COC) for the 100-HR-3 and 100-KR-4 OUs (Figure 1-1), with concentrations exceeding the Federal drinking water standard (DWS) of 100 μg/L; the Washington State groundwater standard of 48 μg/L, and the ambient water quality criterion (AWQC) of 10 μg/L in the hyporheic zone along the Columbia River. Chromium contamination also exists at the 100-NR-2, 100-BC-5, and 100-FR-3 OUs: concentrations at the 100-FR-3 OU are currently below the DWS inland and are below the AWQC in the Columbia River; concentrations at the 100-BC-5 OU are currently below the DWS but are above the AWQC in some locations; and at the 100-NR-2 OU, only one well (199-N-80) exhibited chromium concentrations above the DWS during 2008, with some locations showing concentrations above the AWQC.

Although the primary COC identified in the 100 Areas is hexavalent chromium, additional COCs have been identified for the 100 Areas and their distribution, migration and fate are also subject to characterization and simulation. These COCs include Tritium, Strontium-90, Carbon-14, Nitrate and TCE. Not all COCs are present in each OU. Details on the distribution and transport parameters for each of the various COCs are outside the scope of this report, but are provided in Hanford annual groundwater monitoring reports.

A groundwater flow and contaminant transport model (flow-and-transport model: Figure 1-1) referred to as the 100 Area Groundwater Model (100AGWM) has been developed for the 100 Areas to support evaluations of the migration and fate of identified COCS; the design and evaluation of interim groundwater pump-and-treat remedies; and to design and evaluate the performance of actions taken to provide protection of the Columbia River from COCs discharging to surface water. This report provides details on the development of the 100AGWM, including the conceptual framework; the assignment of parameter values; and the types and sources of information used to support model development and the application of the model in designing and evaluating remedy expansion alternatives throughout the 100 Areas.

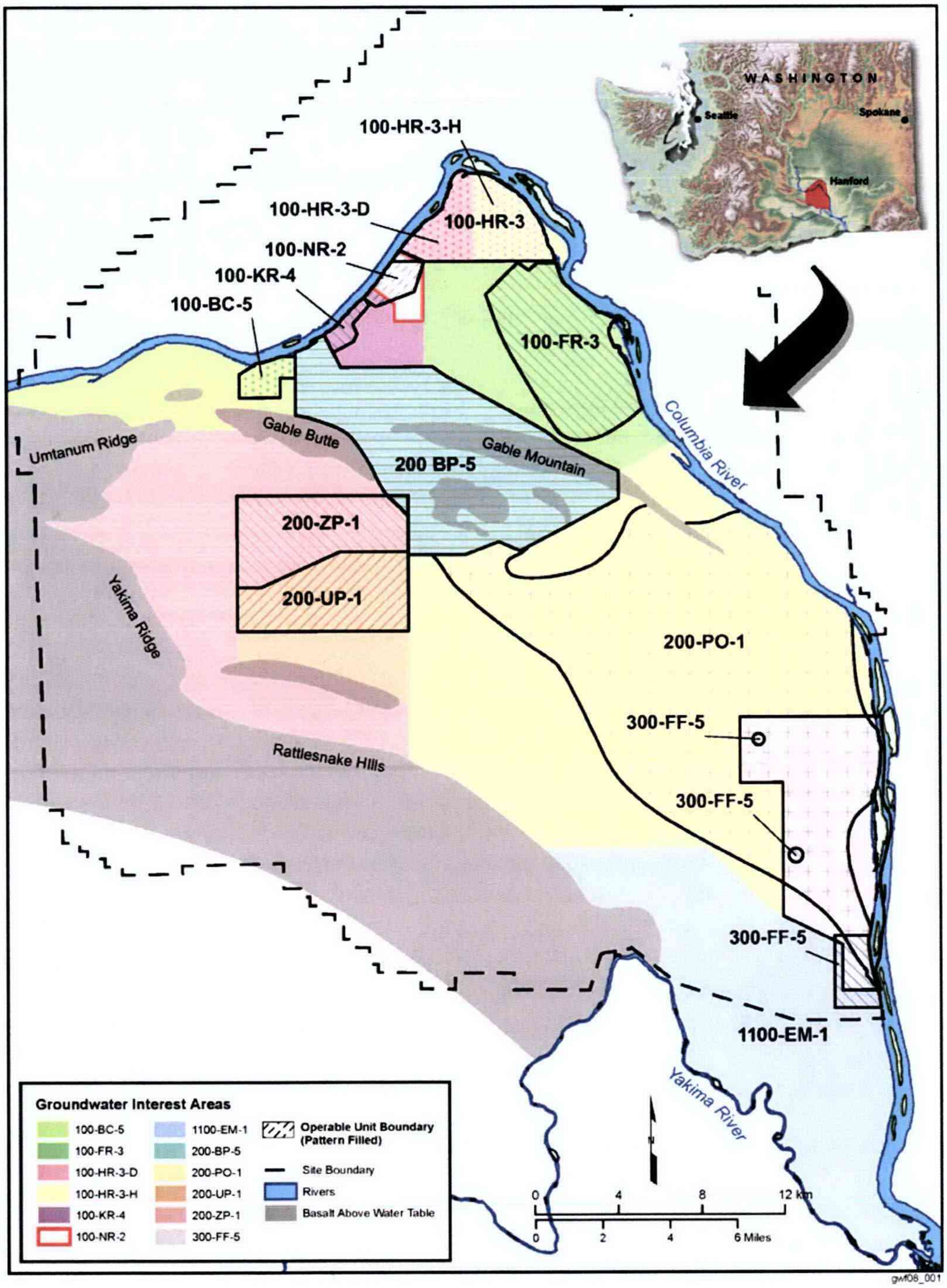
Site investigation is continuing at each of the OUs as part of ongoing characterization efforts, and as part of the Comprehensive Environmental Response, Compensation and Liability Act of 1980 (CERCLA) Remedial Investigation (RI) and Feasibility Study (FS) for the 100 Area OUs which will support final remedy selection and provide the basis for a final Record of Decision (ROD) for each OU. As these new data become available, this Model Documentation report and the groundwater flow and contaminant transport model that it describes will be revised and reissued.

1.1 Regulatory Perspective

The requirement for preparation of this Model Documentation Report is driven primarily by the use of the 100AGWM in support of the active CERCLA RIFS process taking place throughout the 100 Areas, as well as by the broader DOE-RL vision for cleanup of the Hanford Site.

In 1989, representatives from U.S. Department of Energy (DOE), the Washington State Department of Ecology (Ecology), and the U.S. Environmental Protection Agency (EPA) signed the *Hanford Federal Facility Agreement and Consent Order* (Tri-Party Agreement) (Ecology et al. 1989). The Tri-Party Agreement created a cohesive regulatory framework, tentative schedule, and adjudication process to administer environmental remediation activities for the entire Hanford Site. The Tri-Party Agreement provides for a principally CERCLA-based cleanup process and incorporates modifications for *Resource Conservation and Recovery Act* (RCRA)-type activities and/or other items that are better addressed under different federal statutes or Washington State law. The Tri-Party Agreement is composed of a legal agreement, an action plan, and several appendices. Two appendices to the Tri-Party Agreement also provide important context for implementing CERCLA at the Hanford Site. Appendix C of the Tri-Party Agreement provides a list of all known past-practice waste sites to be addressed under the legal and action plan requirements of the agreement. Waste sites on this list are grouped together to form OUs. The OUs are groups of past-practices waste sites that can be characterized, assessed, and remediated as a group. In addition to waste site or source OUs, several Hanford Site groundwater contaminant plumes have been defined as groundwater OUs. Each OU is assigned to either EPA or Ecology as the lead regulatory agency.

The 100 Areas have been subdivided into 22 OUs, including 17 source OUs and 5 groundwater OUs (including 100-HR-3, 100-KR-4, 100-NR-2, 100-FR-3, and 100-BC-5) for the purpose of implementing the CERCLA process. Implementation of the CERCLA process (remedial investigation/feasibility study [RI/FS] and proposed plan) includes final remedial investigation characterization to obtain the final Records of Decision, and construction of the final remedies for the groundwater OUs. RI/FS work plans were developed beginning in early 1990. For each reactor area, RI/FS work plans were prepared initially for a source OU containing liquid waste sites that constitute primary sources of groundwater contamination and the corresponding groundwater OU. Currently the RI/FS process is underway for these OUs and additional RI/FS work plans are prepared to investigate burial ground and other less significant waste site-based OUs. In particular, the DOE Richland Operations Office (RL) and its contractors have undertaken an extensive RI/FS process with the intent of developing final remedies for the 100 Area groundwater OUs. This report is focused on modeling activities relative to the 100 Area River Corridor groundwater OUs, with hexavalent chromium the primary COC.



Source: DOE/RL-2008-66, 2009, *Hanford Site Groundwater Monitoring for Fiscal Year 2008.*

Figure 1-1. Location of 100 Area Groundwater Operable Units in Relation to Other Hanford Site Groundwater Operable Units

1.2 100 Areas Modeling Objectives

Modeling of the subsurface movement of water and contaminants is being conducted in the 100 Areas in support of various efforts to reduce the risk posed to human health and the environment; control the migration of contaminants in groundwater within close proximity to the Columbia River shoreline; maintain compliance with the Tri-Party Agreement; and shrink the footprint of the Hanford Site to a smaller geographic area. As part of these overarching modeling activities, the 100AGWM has been developed and deployed with two quite specific objectives pertaining to the groundwater contamination:

1. Plume remediation: Take necessary actions to remediate chromium groundwater plumes so hexavalent chromium will meet DWSs (Tri-Party Agreement Milestone M-016-110-T02, to be achieved by December 31, 2020). Within the context of the RI/FS, this same goal is extended for the remediation of the other identified COCs in the 100 Areas.

2. River protection: Take actions necessary to contain or remediate hexavalent chromium groundwater plumes so AWQC standards are achieved in the hyporheic zone and river sediments (Tri-Party Agreement Milestone M-016-110-T01, to be achieved by December 31, 2012). For all other identified COCs, DWSs should be achieved in the hyporheic zone and river sediments by December 31, 2016.

Attaining these objectives necessitates the simulation of groundwater flow and the fate-and-transport of contaminants in groundwater throughout the 100 Area OUs. The *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan* (DOE/RL-2008-46, *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan Draft A*) describes the strategy developed for making final decisions to complete cleanup along the River Corridor. Addenda to the work plan outline the goals and strategy for data collection and analyses for each 100 Area OU to develop the RI/FS documentation. To meet the RI/FS needs for each 100 Area OU, the existing 100 Area groundwater model – which encompassed the 100-D, H and K areas – was expanded to extend beyond 100-B/C and 100-F areas, thereby encompassing all 100 Area OUs; and to simulate flow-and-transport in three dimensions. As a result, the current version of the 100AGWM simulates saturated aquifer conditions and contaminant transport in three dimensions in the 100-B/C, 100-K, 100-D, 100-H and 100-F Areas.

1.3 Document Organization

This document is organized as follows:

- Chapter 1: Provides the overarching modeling objectives.
- Chapter 2: Provides background on each of the individual OUs (100-HR-3, 100-KR-4, 100-BC-5, 100-NR-2 and 100-FR-3). Attention is focused on OUs at which hexavalent chromium is the primary COC.
- Chapter 3: Discusses the conceptual models for 100-HR-3, 100-KR-4, 100-BC-5, and 100-NR-2 OUs. The discussion on conceptual model is presented in the context of features, events, and processes (FEPs). The nature and extent of contamination for individual OUs is also presented.
- Chapter 4: Describes the flow and transport properties database.
- Chapter 5: Discusses implementation of the conceptual site model (CSM), the computer codes used, and the parameterization, to construct the 100AGWM.
- Chapter 6: Discusses the 100AGWM flow model calibration.

- Chapter 7: Provides information on the 100AGWM flow model validation.
- Chapter 8: Discusses the principal elements of the contaminant transport modeling methods employed with the 100AGWM.
- Chapter 9: Provides an overview of the 100AGWM assumptions and limitations.
- Chapter 10: Reviews aspects of model configuration management for the 100AGWM.
- Chapter 11: Provides a summary of the 2009 technical peer review panel recommendations and the status of their resolution in the current 100AGWM detailed in this report.
- Chapter 12: Lists the references cited in this report.

2 Site Infrastructure and Process Operations

2.1 Introduction

While the 100 Area reactors were operational, large volumes of Columbia River water were treated with sodium dichromate (to inhibit corrosion of the reactor piping) and used as coolant for the reactors. After a single pass through the reactor - and before discharge to the Columbia River - the coolant water was sent to unlined retention basins to cool and to allow short-lived radioactive contaminants to decay. This approach used for reactor cooling introduced large volumes of process water contaminated with hexavalent chromium into the vadose zone and, ultimately, into the groundwater. In addition, numerous leaks and spills of concentrated sodium-dichromate stock solution occurred during reactor operations, locally introducing much higher concentrations of chromium contamination into the vadose zone and groundwater. The following section describes the physical setting, site infrastructure, and process and operational history for the 100-HR-3, 100-KR-4, 100-BC-5, 100-NR-2, and 100-FR-3 groundwater OUs. The groundwater OUs are referred simply as OUs in this chapter and elsewhere.

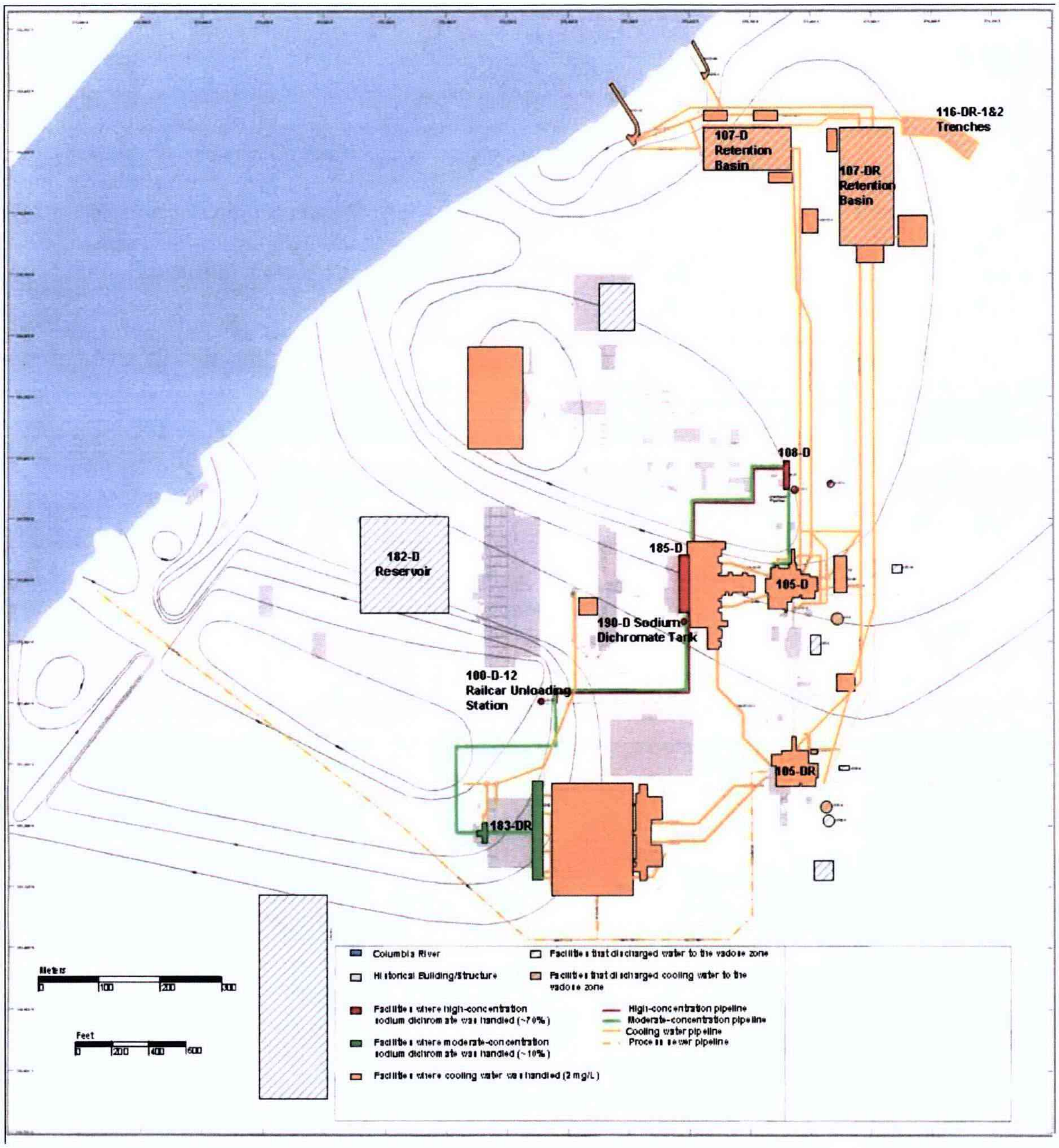
2.1.1 100-HR-3 Operable Unit

Geographically, the 100-HR-3 OU consists of the 100-D Area, 100-H Area, and the Horn in between. The 100-HR-3 OU encompasses the operating areas of the former D and DR Reactors in the100-D Area and the former H Reactor in the 100-H Area (Figure 1-1).

The 100-D Area facilities include cooling water systems, distribution lines, reactors, conveyance, holdup, and discharges (Figure 2-1), which are summarized in *Remedial Process Optimization for the 100-D Area Technical Memorandum Document* (SGW-38338). The sodium-dichromate salts and various solutions were handled at specific locations over the service life of the D and DR Reactors. Locations where source materials of the various concentrations were handled and used are described in SGW-38338. A 2-mg/L sodium-dichromate cooling water solution was used as the single-pass primary coolant in the D and DR Reactors. The reactor coolant was subsequently routed to the 116-DR-9 retention basin and ultimately discharged to the Columbia River at the 100-D-65 and 116-DR-5 outfalls. Decontamination solutions containing sodium dichromate were used in the 108-D Building.

Variable (and generally not well defined) quantities of the various sodium-dichromate solutions are known and/or suspected to have been discharged to the vadose zone in the 100-D Area (SGW-38338). These release events included discharges to the environment, leaks from conveyances, and other unintentional releases, including the following locations (Figure 2-1):

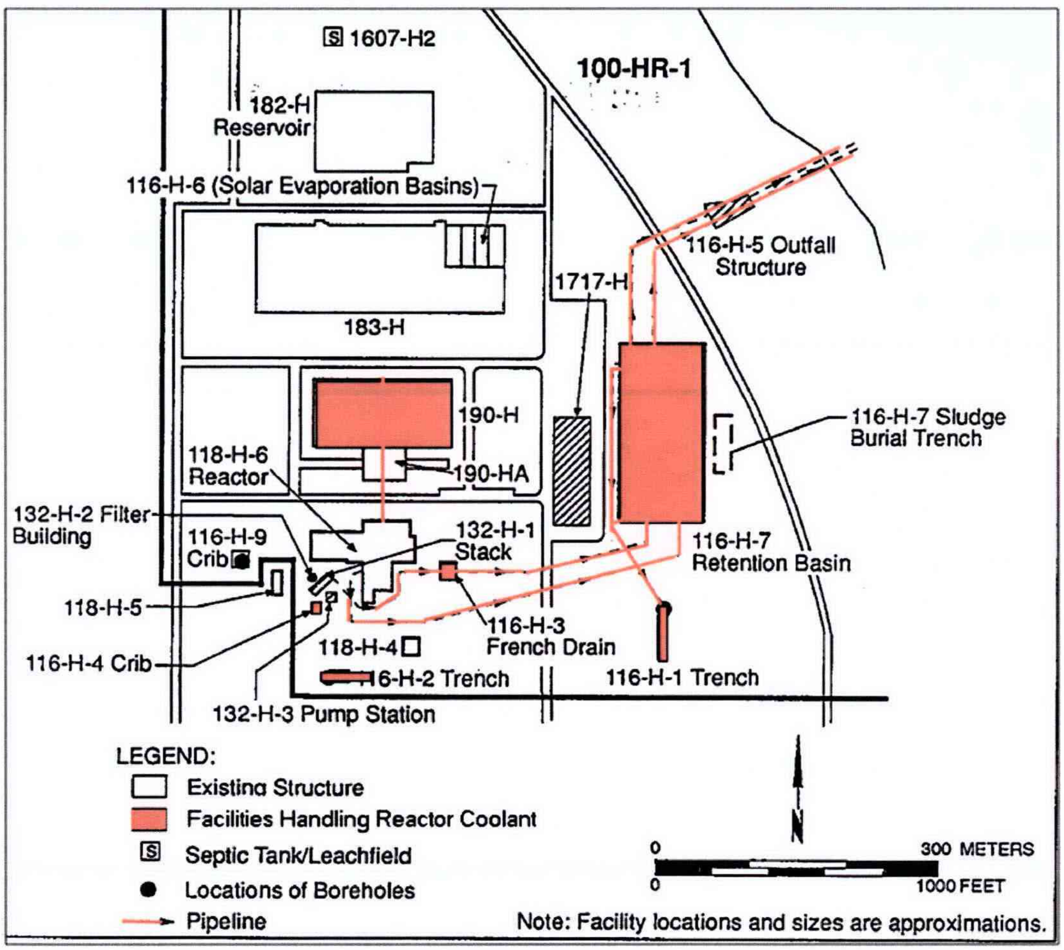
- 107-D retention basin
- 116-DR-1 emergency retention crib
- 108-D Building cribs
- 100-D-31 process sewer
- 100-D-12 railcar/truck unloading station.



Source: SGW-38338, *Remedial Process Optimization for the 100-D Area Technical Memorandum Document.*

Figure 2-1. 100-D Area Location of Facilities Used for Storage, Handling, and Use of Hexavalent Chromium Materials and Solutions

Reactor coolant production for the 100-H Area was far less complex than for the D and DR Reactors. The facilities involved in the reactor coolant process are shown in Figure 2-2. Rather than using multiple mixing steps to progress from highly concentrated chromium solutions to dilute reactor coolant solutions, a one-step process was used at the 100-H Area. Columbia River water was treated for impurities and pumped to the 190-H Building (Figure 2-2), where sodium dichromate was added. The coolant was then pumped through the reactor and piped to the 116-H-7 retention basin for cooling. Two smaller facilities, the 116-H-1 Trench and 116-H-4 Crib (Figure 2-2), also briefly received coolant in the early 1950s. After cooling, the fluid was pumped to the Columbia River and discharged through the 116-H-5 outfall structure (Figure 2-2). In addition to reactor coolant, chromium was also present in equipment decontamination fluids, which were discharged to the 116-H-2 Trench and 116-H-3 french drain (Figure 2-2). Numerous small, solid waste burial grounds were used in the 100-H Area, and some amounts of chromium are likely also present in these facilities.



Source: DOE/RL-93-51, *Limited Field Investigation Report for the 100-HR-1 Operable Unit.*

Figure 2-2. 100-H Area Location of Facilities Used for Storage, Handling, and Use of Hexavalent Chromium Materials and Solutions

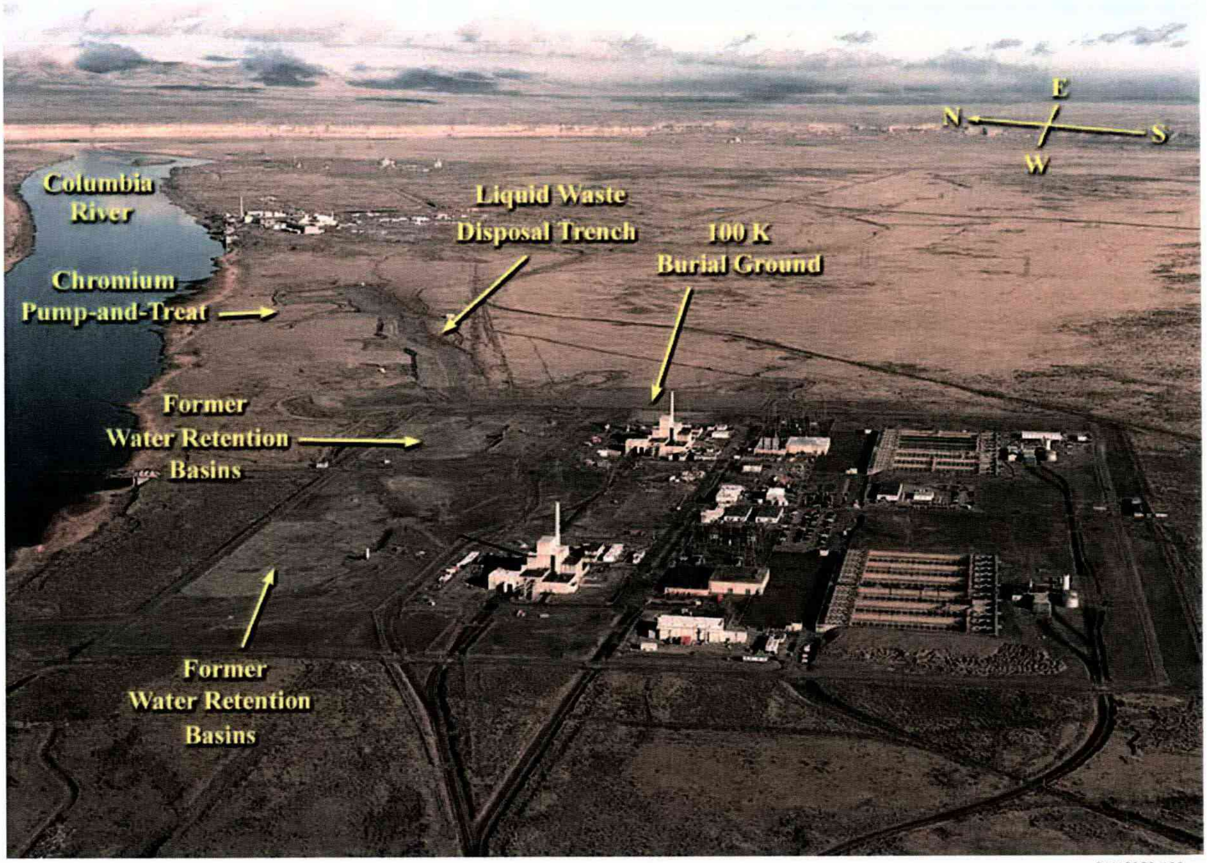
For both the 100-D and 100-H Areas, in compliance with RCRA guidance, a number of treatment, storage and/or disposal units were addressed as part of the deactivation, decommissioning, decontamination, and demolition work. Figure 2-3 shows the 100-H Area after completion of these activities.

Figure 2-3. 100-H Area Following Deactivation, Decommissioning, Decontamination, and Demolition Activities

2.1.2 100-KR-4 Operable Unit

The 100-K Area (Figure 2-4) is the site of two deactivated reactors: KE Reactor, which operated from 1955 to 1971; and KW Reactor, which operated from 1955 to 1970. To generate cooling water solutions for the KE and KW Reactors, concentrated sodium-dichromate feed solutions were processed through an infrastructure system that diluted the higher strength source materials to achieve the required coolant composition (Figure 2-5). Each reactor had a dedicated but identical processing infrastructure. The facilities and processes used to generate, use, and discharge reactor coolant after use are described in the *Remedial Investigation/Feasibility Study Work Plan for the 100-KR-4 Operable Unit, Hanford Site, Richland, Washington* (DOE/RL-90-21).

To begin the process, concentrated sodium-dichromate solutions were brought to the site by railcar and were transferred to 158,987 L (42,000-gal) 120-KW-5 and 120-KE-6 storage tanks (near the 183-KW and 183-KE complexes, located next to the 190-K and 165-K Buildings) that treated and stored water from the Columbia River (Figure 2-5). The solution, frequently referred to as the 70 percent solution, had a pH of approximately 1.5 to 2, chromium concentrations of about 8.96 mol/L (or 466 g/L) (PNNL-17674, *Geochemical Characterization of Chromate Contamination in the 100 Area Vadose Zone at the Hanford Site*), and specific gravity of approximately 1.7 g/cm^3. Some length of piping carried the treated river water (70 percent solution) to clearwell tanks at the northern end of the 183-KW/KE facilities. Beyond this point, 70 percent solution was not present in the coolant production process or discharge infrastructure.



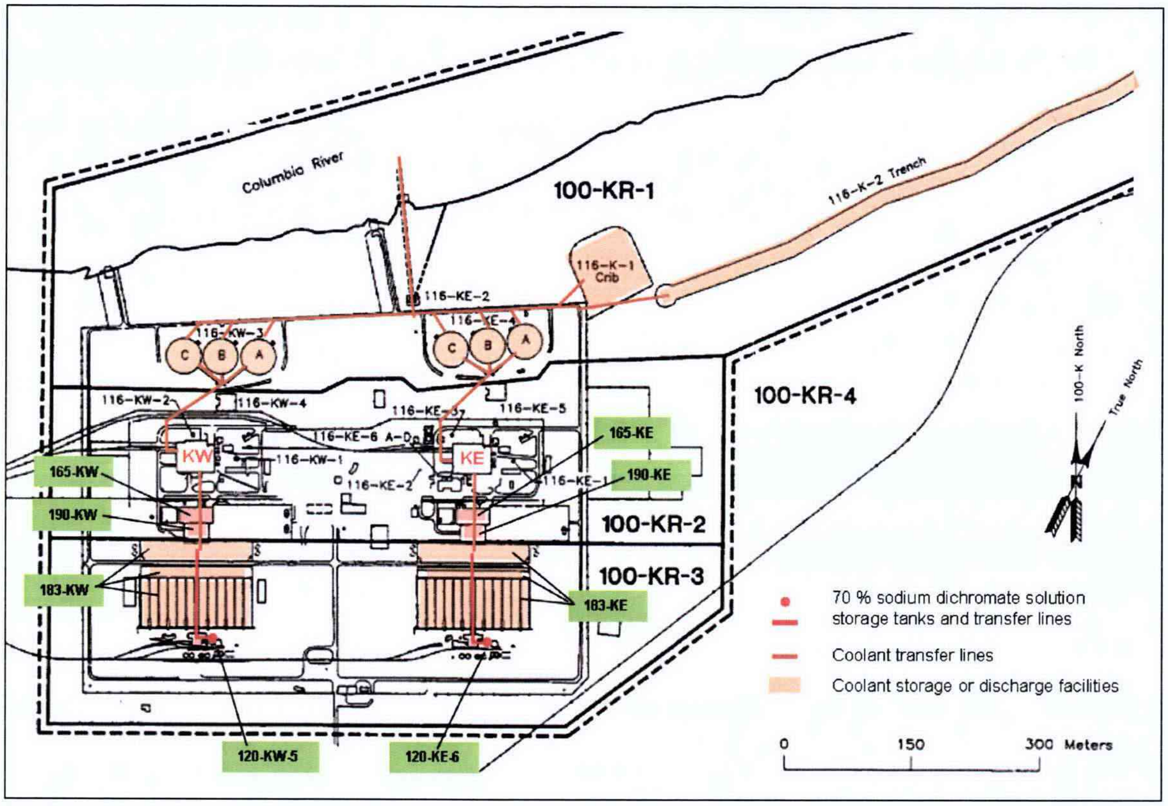
Source: PNNL-14031, *Evaluation of Potential Sources for Tritium Detected in Groundwater at Well 199-K-111A, 100-K Area.*

Figure 2-4. Aerial Photograph of the 100-K Area

During transfer from the railcars to the storage tanks, some sluicing of fluid into a nearby drain and other unintentional spills occurred, as indicated by yellow-stained soil around the tanks. The piping beneath the 183-KW/KE facilities (Figure 2-5) also provided opportunities for subsurface leaks. The quantities of solution lost from these initial stages of coolant-production infrastructure are unknown, but the locations from which the 70 percent solution could have been released into the subsurface is limited.

2.1.3 100-BC-5 Operable Unit

The 100-BC-5 OU (Figure 2-6) contains the former B and C Reactors. The B Reactor was the first of three original Hanford Site reactors built during World War II as part of the Manhattan Project; the C Reactor was built 8 years after B Reactor. In addition to its plutonium-production mission, C Reactor was used for reactor physics and operational testing, and it was a pilot-scale version for the reactors at the 100-K Area.



Source: DOE/RL-2008-46, *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan.*

Figure 2-5. Facilities in the 100-K Area That Produced, Stored, or Transferred Liquid Sodium-Dichromate Solutions

The reactors were supported by multiple facilities associated with services for water treatment, air filtration, nuclear fuel handling, effluent disposal, laboratories, and various other buildings. Initial cleanup activities began soon after the reactors were deactivated in 1968 (B Reactor) and 1969 (C Reactor). Follow-up housekeeping and decommissioning activities began in 1973 as part of a sitewide initiative. This effort progressed as resources allowed through 1990 with buildings demolished, surplus equipment salvaged or redeployed, and minimal active operations maintained. The majority of the reactor ancillary and support facilities have been demolished and/or removed (see Figures 2-6 and 2-7).

At the 100-B/C Area, liquid and solid wastes from reactor operations and associated facilities were released to the soil column and to the Columbia River. Sources of contamination includes liquid waste sites, burial grounds, unplanned release sites, facilities/structures, and pipelines/outfalls. A complete list of 100-B/C Area facilities and waste sites (including descriptions, histories, and classification statuses) is provided in *Integrated 100 Area Remedial Investigation Study/Work Plan, Addendum 3: 100-BC-1, 100-BC-2, and 100-BC-5 Operable Units* (DOE/RL-2008-46-ADD3, Appendices C and D).

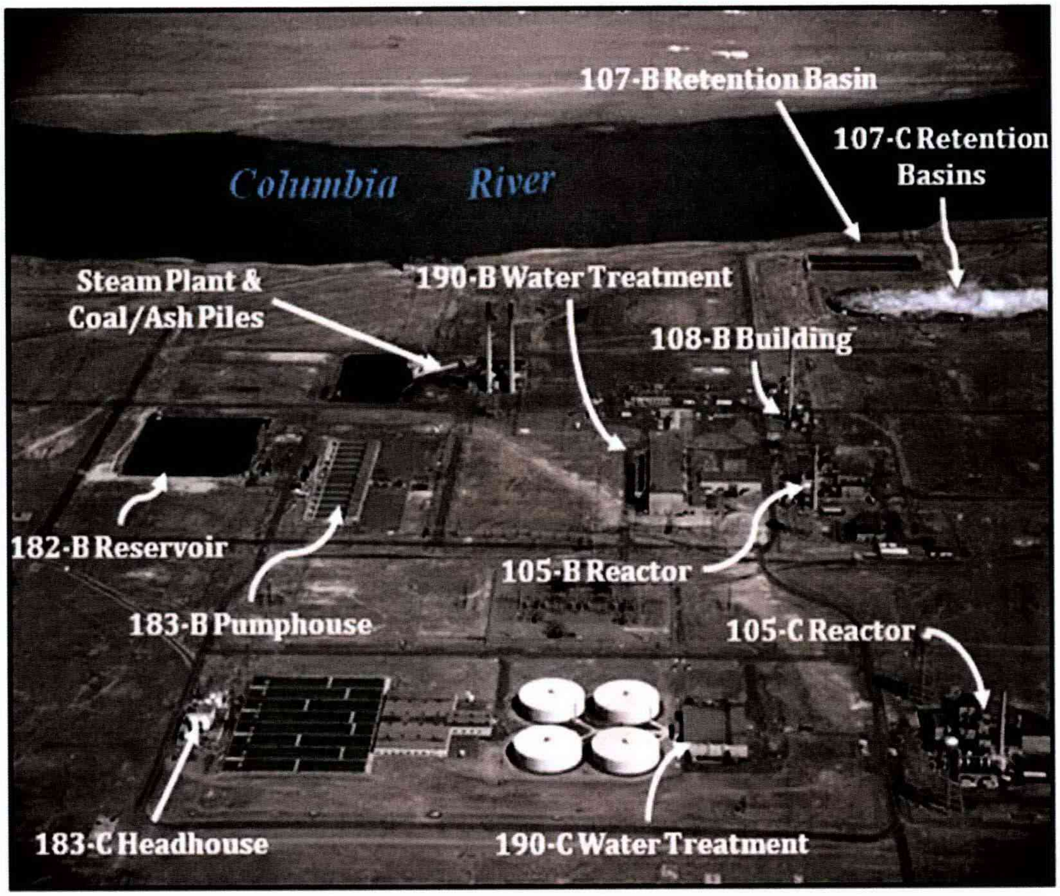


Figure 2-6. 100-B/C Area Major Features During Reactor Operation (1966)

Figure 2-8 shows the primary liquid waste disposal features within the 100-B/C Area. One facility of particular interest regarding its potential contribution to groundwater contaminant distribution is the 182-B reservoir (Figures 2-6 and 2-7). The 182-B reservoir is an operating system that has affected contaminant transport and groundwater flow. Leaks from the 182-B reservoir are potentially affecting groundwater in the 100-B/C Area and providing a potential transport pathway for contaminants in the soils and groundwater.

Facilities that were used during reactor operations make up most of the demolished and removed structures. These structures consist of retention basins, reactor stacks, office and storage buildings, maintenance shops, process plants, electric substations, storage tanks, and pump stations. Active facilities include a mobile office (MO-474), an electric substation (151-B), a pump station (181-B), and a process plant (182-B), which supplies water to the 200 Area. The five inactive facilities in the 100-B/C Area are the B Reactor building, C Reactor building, 116-B exhaust stack, 119-B laboratory, and 181-C pump station.

Figure 2-7. More Recent (2006) Conditions at the 100-B/C Area

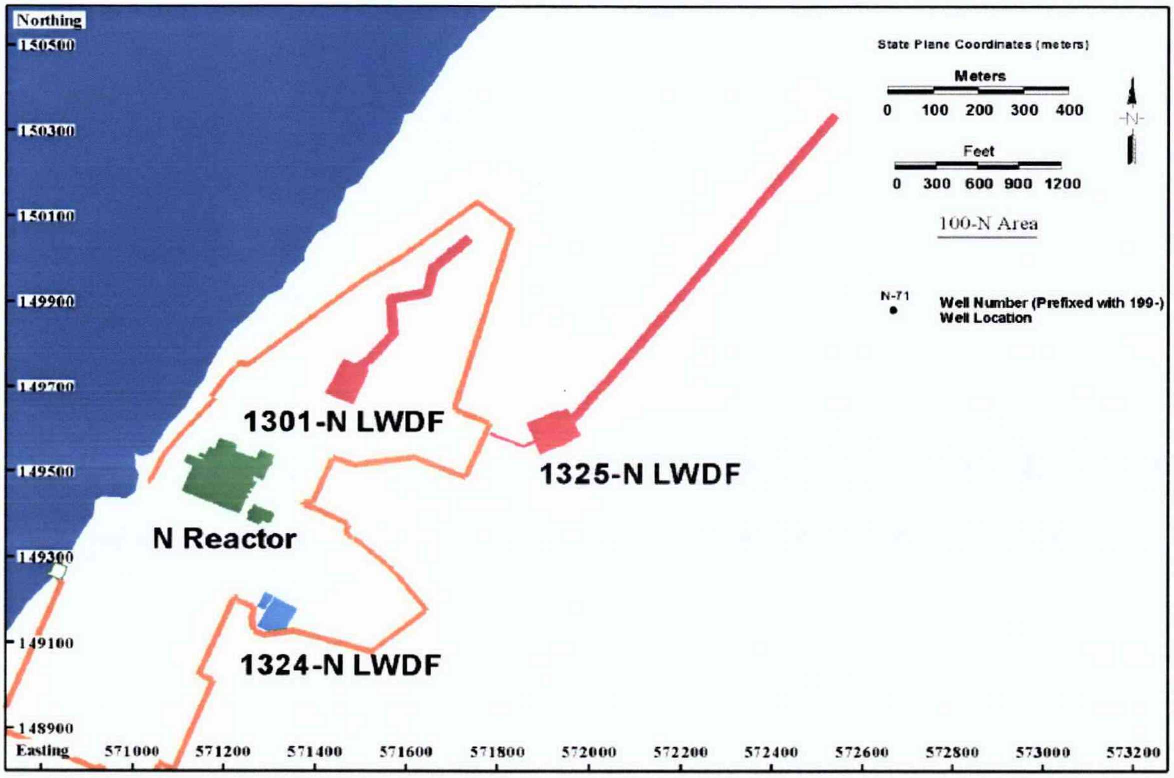
2.1.4 100-NR-2 Operable Unit

The 100-NR-2 OU (Figure 1-1) includes the former N Reactor, which was constructed in 1963. The N Reactor was unique among the nine Hanford Site production reactors in its use of a heat-exchange cooling system that greatly reduced the release of contaminants to the Columbia River in comparison to the other eight single-pass reactors. The primary coolant (deionized water) was passed through the N Reactor multiple times (roughly 100 cycles, based on a 1 percent continuous replacement), which resulted in higher levels of some radionuclides in the primary coolant water compared to Hanford's single-pass reactors.

During operation, contaminated water from the cooling loop of the reactor and other related sources was directed to the 1301-N (116-N-1 Crib, which operated from 1963 to 1983) and the 1325-N (116-N-3 Crib, which operated from 1983 to 1991) liquid waste disposal facilities (LWDFs) located on the bluff above the Columbia River (Figure 2-9). With closure of the final single-pass reactor in 1971, the N Reactor was the only operating production reactor. Although direct discharge of radionuclides and chemicals to the Columbia River was minimal, substantial volumes of contaminated water were discharged to the LWDFs. As a result, contaminants became dispersed from the soil column beneath the LWDFs to the riverbank springs on the 100-N Area shoreline. Production operations at N Reactor ceased in 1985, resulting in a dramatic decrease in the volume of water discharged to the LWDFs, thus greatly reducing discharge volumes to the 100-N Area riverbank. The N Reactor was deactivated in 1987.

Figure 2-8. Southern View of the 100-B/C Area Showing Primary Liquid Waste Disposal Features, April 2002

The majority of the ancillary reactor and support facilities that were constructed to serve 100-N Area nuclear reactor processes and operations remain standing (Figure 2-10). Water treatment chemicals (e.g., aluminum sulfate, sulfuric acid, hydrazine, chlorine, and sodium dichromate) were used and stored at and near water treatment buildings and were transferred through influent and effluent process piping. Preparations using these and other chemicals prevented corrosion and were used to produce solutions for decontamination activities.



Source: DOE/RL-2006-26, *Aquatic and Riparian Receptor Impact Information for the 100-NR-2 Groundwater Operable Unit.*

Note: The 100-N Area boundary is shown in the figure in yellow.

Figure 2-9. 1301-N (116-N-1 Crib) and 1325-N (116-N-3 Crib) Liquid Waste Disposal Facilities for the 100-NR-2 Operable Unit

Source: DOE/RL-2008-46-ADD5, *Integrated 100 Area Remedial Investigation Study/Work Plan, Addendum 5: 100-NR-1 and 100-NR-2 Operable Units.*

Figure 2-10. Aerial View of the100-N Area (2002)

2.1.5 100-FR-3 Operable Unit

The F Reactor operated from 1945 to 1965. Figure 2-11 shows an aerial view of 100-F Area during the production days. The F Reactor was supported by multiple facilities associated with services for water treatment, air filtration, nuclear fuel handling, effluent disposal, laboratories, and administrative buildings (WHC-SD-EN-TI-169, *100-F Reactor Site Technical Baseline Report Including Operable Units 100-FR-1 and 100-FR-2*). With regard to soil and groundwater contamination, these services generated various types of waste that were either discharged to the Columbia River; directed to unlined cribs, trenches, or another engineered structure; or buried in unlined burial grounds onsite.

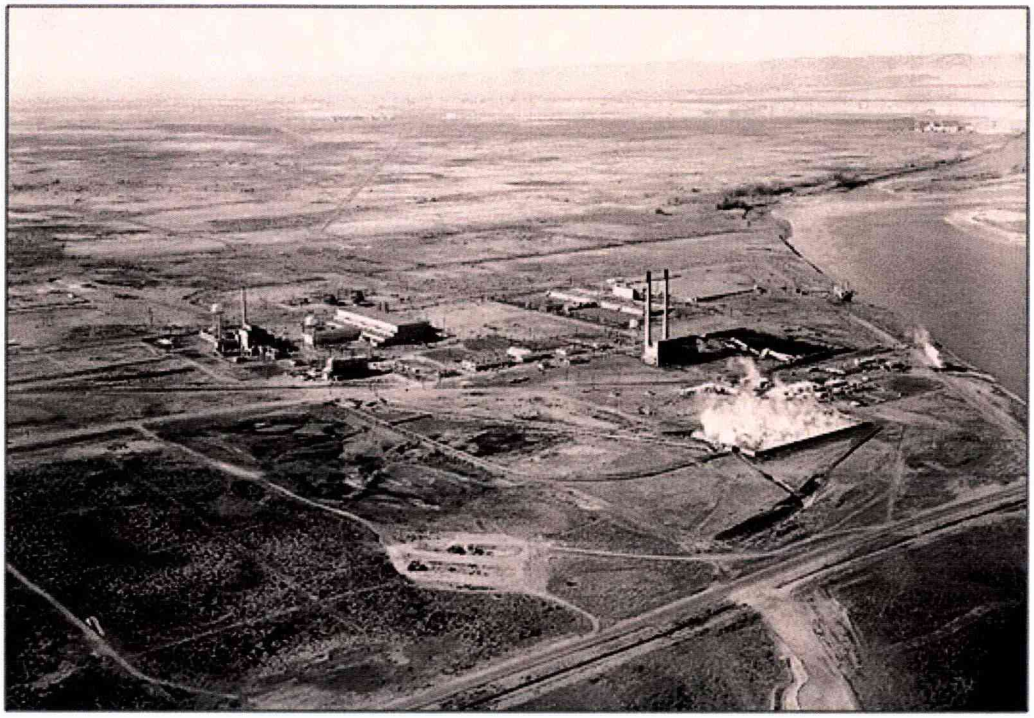


Figure 2-11. Areal View of 100-F Area During Production (1962)

The 100-F Area sources of contamination include liquid waste sites, burial grounds, unplanned release sites, facilities/structures, and pipelines/outfalls. A complete list of 100-F Area facilities and waste sites (including descriptions, histories, and classification statuses) is provided in Appendices C and D of DOE/RL-2008-46-ADD4, *Integrated 100 Area Remedial Investigation Study/Work Plan, Addendum 4: 100-FR-1, 100-FR-2, 100-FR-3, 100-IU-2, and 100-IU-6 Operable Units*. The facilities used during reactor operations, including those that have been demolished and removed, consisted of retention basins, reactor stacks, office and storage building, maintenance shops, process plants, electric substations, storage tanks, and pump stations. Figure 2-12 provides an aerial view of 100-F Area showing the excavated waste sites.

Hexavalent chromium contamination is of particular concern because of its widespread use in water treatment in the 100 Area reactors. Sodium dichromate, the source of the hexavalent chromium, was delivered and used in both dry chemical powder and concentrated liquid forms. Hexavalent chromium is present in groundwater at levels above the aquatic standard, although hexavalent chromium contamination at the 100-F Area does not exhibit the same levels of contamination as observed at the 100-D Area, for example.

Figure 2-12. Areal View of the 100-F Area Showing Excavated Waste Sites (2007)

A subsequent mission to plutonium production that was undertaken in and around F Reactor was a biological laboratory to examine the effects of radiation and radioactive contamination on plants, animals, and fish. The experimental animal farm was located in the 100-F Area and operated from 1945 until 1976. The experimental animal farm and its operations produced contaminated animal/plant waste that was disposed onsite. Several isotopes were used in these experiments, but strontium-90 is of particular concern in this case because the concentration remains elevated in groundwater above the drinking water threshold.

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3 Site Conceptual Model

3.1 Features, Events, and Processes (FEPs)

Conceptual models are evolving hypotheses that identify the important features, events, and processes controlling fluid flow and contaminant transport at a specific field site and in the context of a specific problem. In general, a conceptual model description should consist of a detailed characterization of the following:

- Features: Such as site geology and media heterogeneity, as described by spatial variability of the physical and chemical properties.
- Events: Such as natural recharge, manmade discharges, process history, inventory of materials discharged to ground, and remediation actions (e.g., RPO pump-and-treat systems).
- Processes: Such as the dynamics of soil moisture movement in heterogeneous media, , and stream/aquifer interaction.

The conceptual models help to provide rationale regarding the nature and extent of contamination at various OUs.

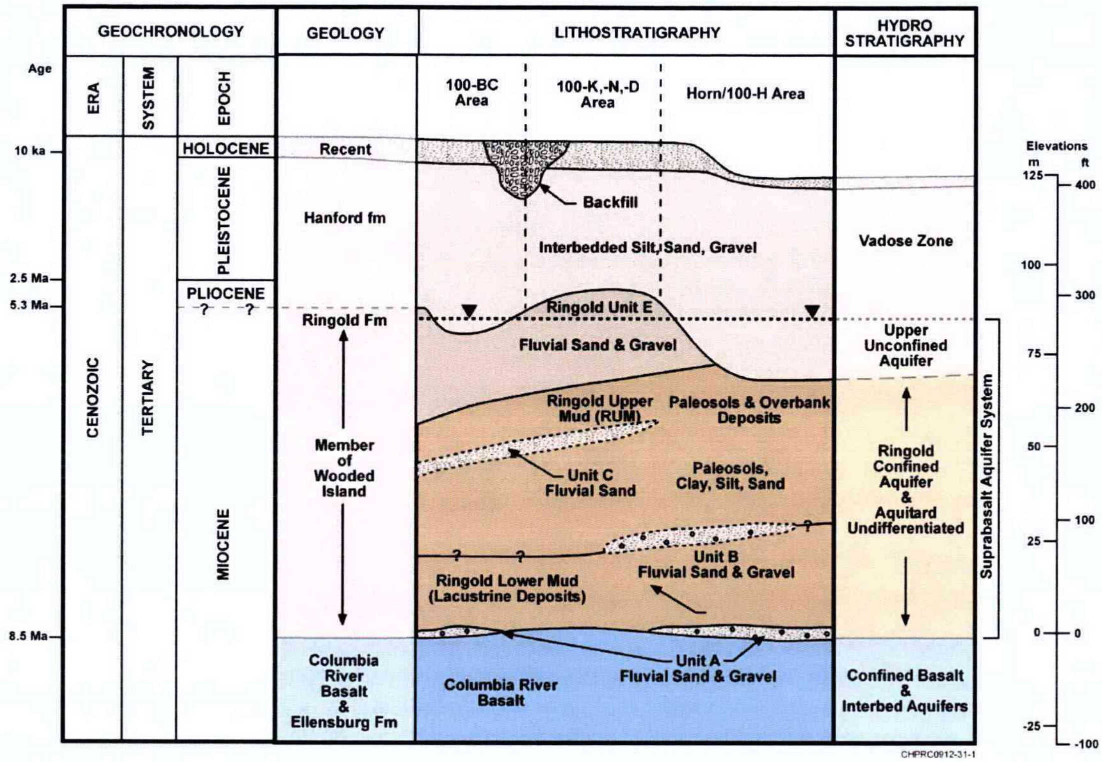
3.2 Features

The geologic features for individual groundwater OUs (i.e., 100-HR-3, 100-KR-4, 100-BC-5, 100-NR-2, and 100-FR-3) are discussed in the following subsections. The important features for the 100 Area vadose zone are also briefly discussed.

3.2.1 100-HR-3 Operable Unit Hydrogeology

As discussed below, available site characterization information is summarized and detailed tables are included for each OU presenting the elevations for hydrologically significant stratigraphic units. When combined, these data (as discussed later) serve as the building blocks for the 100 Areas groundwater model. For example, the contact between the Ringold Formation Unit E and the Hanford formation (Hanford/Ringold contact) is important because the saturated hydraulic conductivity of the Hanford formation gravel-dominated sequence is typically higher than the more compacted and locally cemented Ringold Unit E and is significantly higher than the deeper Ringold Formation undifferentiated fine-grained units (i.e., Ringold Upper Mud unit [RUM]). From a modeling perspective, it is important to identify where the Hanford/Ringold contact surface occurs below the water table and/or where it occurs as buried paleo-flood or river channels because these features can potentially form preferential pathways for contaminated groundwater to migrate to the Columbia River (PNNL-14702, *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis*). As discussed below for each of the individual OUs, hydrogeologic surface (structure) maps of the Hanford/Ringold contact, as well as the RUM, are included.

The generalized geology beneath the 100 Areas (Figure 3-1a) comprises the Hanford formation, Ringold Formation, Columbia River Basalt Group, and the Columbia River Basalt Group sedimentary interbeds (Ellensburg Formation) (WHC-SD-EN-TI-132, *Geologic Setting of the 100-HR-3 Operable Unit, Hanford Site, South-Central Washington*; and DOE/RL-93-43, *Limited Field Investigation Report for the 100-HR-3 Operable Unit*). The descriptions below are paraphrased from the *Hydrogeological Summary Report for the 600 Area Between 100-D and 100-H for the 100-HR-3 Groundwater Operable Unit* (DOE/RL-2008-42). Figure 3-1b presents a schematic cross-section illustrating the regional character of the hydrogeology across the 100 Areas.



Source: SGW-44022, *Geohydrologic Data Package in Support of 100-BC-5 Modeling.*

Figure 3-1a. Generalized 100 Areas Hydrogeology

The uppermost unconfined aquifer is contained within Ringold Formation and/or Hanford formation sediment and ranges in thickness from approximately 6 to 30 m (16.5 to 98 ft). Regionally, groundwater flows from areas of higher elevation upgradient (south) of the boundaries of the OUs near Gable Mountain and Gable Butte in a northerly direction, discharging to the Columbia River. The base of the unconfined aquifer is well defined by the surface of the low-permeability RUM, which underlies Ringold Unit E to the west (100-B/C to 100-D Area) and Hanford formation sediment to the east (100-H and 100-F Areas) (Figures 3-1a, 3-1b, and 3-2). Table 3-1 provides details on 100-HR-3 OU supporting structure maps and cross-sections.

The geologic units that comprise the uppermost unconfined aquifer (Figure 3-1) contain the bulk of the contaminants migrating beneath the 100 Area OUs. The description for geologic units begins with the youngest units at the surface that are within the overlying vadose zone, progressing into the older units, and then to the lower confining unit at the base of the unconfined aquifer.

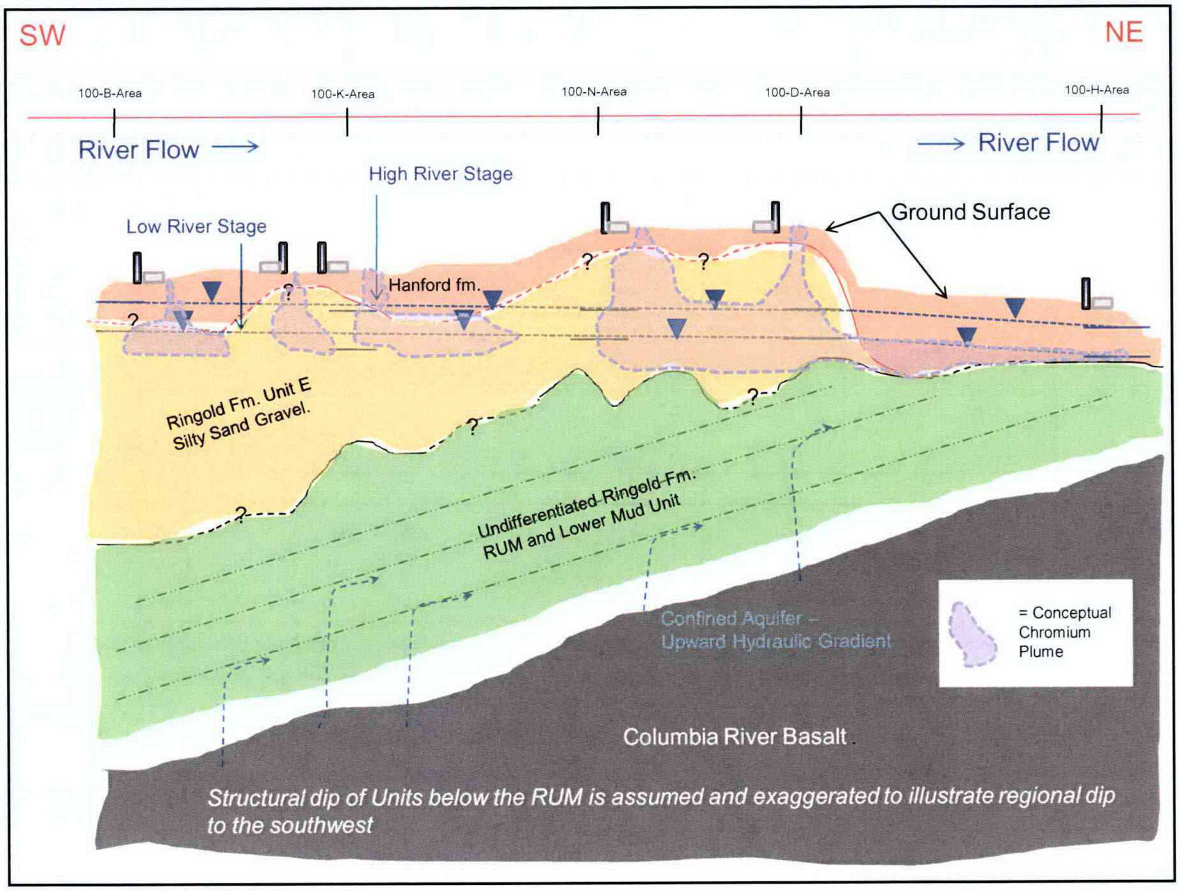


Figure 3-1b. Schematic Hydrogeologic Conceptualization Along the Columbia River Reach

Backfill and Holocene (Recent) Deposits

Recent backfill sand and gravel and/or Holocene deposits of eolian loess, silt, sand, and gravel form surficial deposits across the 100 Areas (Figure 3-1). Construction backfill is located near manmade structures and varies in depth, depending on the excavation depth of waste sites and building foundations. Additionally, backfill material may cover larger graded areas to a depth of up to 0.3 m (1 ft). Because of the anthropogenic activities associated with construction of the reactors and supporting facilities, the Holocene deposits may have been removed or altered and, outside of those areas, Holocene deposits are more prevalent (up to at least 1 m [3 ft] thick).

Hanford Formation

The Hanford formation consists of gravel, sand, and silt deposited by cataclysmic Ice Age floodwaters (Figure 3-1) during the Pleistocene epoch (DOE/RW-0017, *Consultation Draft, Site Characterization Plan Reference Repository Location, Hanford Site, Washington*). The Hanford formation is divided into three facies: (1) gravel-dominated, (2) sand-dominated, and (3) interbedded sand to silt-dominated (DOE/RL-2002-39, *Standardized Stratigraphic Nomenclature for Post-Ringold-Formation Sediments Within the Central Pasco Basin*). Of the three facies, the gravel-dominated facies is predominant in the 100 Areas. The Hanford formation sediment thicknesses range from 0 m to greater than 25 m (0 to 82 ft) (Figure 3-1b). The unit appears to be the thickest in the southwest-central portion of the 100 Areas and generally thins to the north and east. The Hanford formation is typically unconsolidated and disconformably overlies fluvial, gravel-dominated strata of Ringold Unit E in the far western portion of the 100 Areas, and it disconformably overlies silt and clay of the RUM throughout the eastern region of the 100 Areas beginning just east of the D Reactor area (Figure 3-1b). Figure 3-2 illustrates this hydrogeologic transition from saturated Ringold Formation to saturated Hanford formation sediment and also provides a conceptual understanding of contaminant migration across the region.

Ringold Formation

Within the 100 Areas, the Hanford formation is underlain by Ringold Formation sediments. The Hanford formation disconformably overlies either the fluvial gravel referred to as Unit E or the lower energy sand, silt, and clay interval referred to as the RUM (Figure 3-1b). North and east of the 100-D Area, the Ringold Unit E is mostly absent, and the top of the Ringold Formation consists of the RUM that stratigraphically underlies Unit E (WHC-SD-EN-TI-132; BHI-00184, *Miocene- to Pliocene-Aged Suprabasalt Sediments of the Hanford Site, South-Central Washington*). Thin remnants of Ringold Unit E have been encountered sporadically across the Horn, ranging in thickness from 0.3 to 3.2 m (1 to 10.5 ft). Elsewhere across the 100 Areas, generally west of the 100-D Area, Ringold Unit E sediment forms the top of the Ringold Formation. Where present beneath the 100 Areas, the top of Ringold Unit E ranges in elevation between approximately 70 m (230 ft) to greater than 135 m (443 ft) (North American Vertical Datum of 1988 [NAVD88]). Ringold Unit E ranges in thickness from greater than 50 m to 0 m (greater than 164 ft to 0 ft) and generally thins toward the east on the continuously rising (shallower) RUM surface (Figure 3-2). The Unit E is truncated near the eastern boundary of the 100-D Area and does not exist to any great extent east of that location. At this location and eastward toward the Columbia River, the uppermost Ringold Formation is the RUM (Figures 3-2 and 3-4). Across the 100 Areas from west to east along the Columbia River, the RUM surface elevation ranges from less than 70 m (230 ft) near the 100-B/C Area to more than 116 m (381 ft) at the 100-D Area. Eastward across the remainder of the Horn, the top of the RUM is encountered between 115 and 104.5 m (377.3 to 342.8 ft) elevation (NAVD88). Across the Horn, east of the 100-D Area, the contact with the overlying Hanford formation appears generally flat-lying, which is likely due to extensive erosion and removal of the Ringold Unit E caused by cataclysmic flooding and limited erosion into the RUM.

Hanford/Ringold Contact

Hanford formation gravels overlie the Ringold Formation sediment across the entire 100-HR-3 OU. Pleistocene-age cataclysmic glacial outburst floods have eroded into the older Ringold Formation sediment and reworked the Ringold surface. Hanford formation sediment was subsequently deposited over the Ringold Formation sediment erosional surface, and the contact surface (disconformity) between the overlying Hanford formation and underlying Ringold Formation forms several hydrogeologic flow boundaries that constrain the uppermost unconfined aquifer. These boundaries are illustrated on the conceptual cross-section and Hanford/Ringold contact surface maps (Figures 3-2, 3-3, and 3-4). This interpretation (Figures 3-2 and 3-4) is based on information from the borehole logs (Table 3-1), aquifer test results, temporal head data, geographic plume shape, and the prominent topographic surface expression of the paleo-erosional features across the Horn.

The most significant geologic change affecting aquifer flow dynamics occurs at the erosional truncation of Ringold Unit E (Figure 3-2), located along the eastern boundary of the 100-D Area (within which the Hanford formation overlies Ringold Unit E). East of the 100-D Area, where the Ringold Unit E has been removed by erosion (Figure 3-4), the Hanford formation disconformably overlies the RUM. The surface of the RUM (Figure 3-5) represents the base of the uppermost unconfined aquifer across the entire 100-HR-3 OU.

Table 3-1. 100-HR-3 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-40781, Rev. 1)

Well Number	Hanford Well ID	Ground Elev. NAVD88 (m) (Disc Z or Brass Cap)	Total Depth (ft bgs)	Top Ringold Formation Rwie (Unit E) (ft bgs)	Top Ringold Formation Rwie (Unit E) (m bgs)	Top RUM (ft bgs)	Elev. Ringold Formation Rwie (Unit E) (m amsl)	Top RUM (m bgs)	Elev. RUM (m amsl)	Elev. Hanford/Ringold Formation Contact (m amsl)	Geologist/Data Source	Comments/ Observations
199-D2-11	—	143.451	114	TBD	—	110.0	—	33.53	109.92	TBD	S. Petersen; SGW-38757	—
199-D2-11	C5394	143.451	114	90	27.4	110	116.0	33.5	109.92	116.0	Williams; borehole log	—
199-D2-3	A5553	—	30	—	—	—	—	—	—	N/A	—	No data; lost well
199-D2-4	A5554	—	33	—	—	—	—	—	—	N/A	—	No data; lost well
199-D2-8	C3040	143.605	N/A	51	15.5	NDE	128.1	NDE	<112.8	128.1	Schalla; borehole log	—
199-D3-1	A5555	—	17	NDE	NDE	NDE	NDE	NDE		NDE	Williams; borehole log	Inconclusive (drill log)
199-D4-19	B8746	143.118	110.5	61.5	18.7	110.0	124.4	33.5	109.59	124.4	BHI-01309	—
199-D4-20	B8750	143.556	107.5	63.0	19.2	105.0	124.4	32.0	111.55	124.4	BHI-01309	—
199-D4-21	B8755	143.650	99.0	49.0	14.9	97.5	128.7	29.7	113.93	128.7	BHI-01309	—
199-D5-12	A4569	143.741	91	48.0	14.6	89.0	129.1	27.12	116.62	129.1	Williams; borehole log	Gamma and drill log
199-D5-13	A4570	143.648	97.3	N/A	N/A	>97.3	N/A	>29.7	<113.95	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-14	A4571	143.854	101	N/A	N/A	>101	N/A	>30.8	<113.1	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-15	A4572	143.897	101.8	46.0	14.0	101.0	129.9	30.77	113.12	129.9	Williams; borehole log	—
199-D5-16	A4573	144.448	99	N/A	N/A	>99	N/A	>30.2	<114.3	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-17	A4574	143.258	115	N/A	N/A	103.5	N/A	31.6	111.7	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-18	A4575	142.578	100.5	N/A	N/A	99	N/A	30.2	112.4	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-19	A4576	141.998	95	N/A	N/A	94.5	N/A	28.8	113.2	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-20	A4577	142.968	103.3	N/A	N/A	101	N/A	30.8	112.2	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-32	C4185	143.136	105.78	N/A	N/A	105	N/A	32	111.1	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D5-33	C4186	143.409	104.18	55	16.8	103	126.6	31.4	112.01	126.6	Martinez; borehole log	—
199-D5-34	C4187	144.519	107.45	54	16.5	105	128.1	32.0	112.52	128.1	Weekes; borehole log	—
199-D5-36	B8744	143.115	103.0	47.0	14.3	98.0	128.8	29.9	113.24	128.8	BHI-01309	—
199-D5-37	B8745	143.066	99.5	46.0	14.0	94.5	129.0	28.8	114.26	129.0	BHI-01309	—
199-D5-38	B8747	143.959	110.0	54.0	16.5	105.0	127.5	32.0	111.96	127.5	BHI-01309	—
199-D5-39	B8748	143.977	108.0	ND	ND	103.0	ND	31.4	112.58	112.58	BHI-01309	—
199-D5-40	B8749	143.976	109.5	74.0	22.5	106.0	121.4	32.3	111.67	ND	BHI-01309	—
199-D5-41	B8751	143.434	109.5	50.0	15.2	104.5	128.2	31.84	111.59	128.2	Walker; borehole log	—
199-D5-41	B8751	143.434	109.5	50.0	15.2	104.5	128.2	31.9	111.58	128.2	BHI-01309	—
199-D5-42	B8752	143.849	109.5	48.0	14.6	106.0	129.2	32.30	111.55	129.2	Walker; borehole log	—
199-D5-42	B8752	143.849	109.5	48.0	14.6	106.0	129.2	32.3	111.54	129.2	BHI-01309	—
199-D5-43	B8753	143.840	112.5	ND	ND	107.0	ND	32.6	111.23	ND	BHI-01309	—

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Well Number	Hanford Well ID	Ground Elev. NAVD88 (m) (Disc Z or Brass Cap)	Total Depth (ft bgs)	Top Ringold Formation Rwie (Unit E) (ft bgs)	Top Ringold Formation Rwie (Unit E) (m bgs)	Top RUM (ft bgs)	Elev. Ringold Formation Rwie (Unit E) (m amsl)	Top RUM (m bgs)	Elev. RUM (m amsl)	Elev. Hanford/Ringold Formation Contact (m amsl)	Geologist/Data Source	Comments/ Observations
199-D5-44	B8754	142.658	100.0	47.5	14.5	95.2	128.2	29.0	113.64	128.2	BHI-01309	—
199-D5-93	C4672	143.61	109	N/A	N/A	109	N/A	33.2	110.39	TBD	Walker; borehole log	—
199-D5-97	C5390	143.724	113.5	TBD	—	109.0	—	33.22	110.50	TBD	S. Petersen; SGW-38757	—
199-D5-98	C5391	142.969	113.4	57	17.4	108.0	125.6	32.92	110.05	125.6	S. Petersen; SGW-38757	—
199-D5-99	C5392	143.991	115	TBD	—	109.5	—	33.38	110.61	TBD	S. Petersen; SGW-38757	—
199-D5-102	C5398	143.808	113.5	TBD	TBD	108.0	TBD	32.92	110.89	TBD	S. Petersen; SGW-38757	—
199-D5-103	C5399	143.606	117	60	18.3	110.7	125.3	33.74	109.87	125.3	S. Petersen; SGW-38757	—
199-D5-104	C5400	144.048	116	N/A	N/A	110.3	N/A	33.62	110.43	TBD	S. Petersen; SGW-38757	—
199-D5-106	C5511	143.674	107.2	50	15.2	107	128.4	>32.6	<111.1	128.4	Rincon; borehole log	—
199-D5-119	C5933	144.007	113.6	78	23.8	110.0	120.2	33.53	110.48	120.2	S. Petersen; SGW-38757	—
199-D5-120	C5934	143.663	112.4	79	24.1	108.0	119.6	32.92	110.74	119.6	S. Petersen; SGW-38757	—
199-D5-121	C5935	143.77	111.8	80	24.4	107.0	119.4	32.61	111.16	119.4	S. Petersen; SGW-38757	—
199-D5-122	C5936	143.674	112.3	74	22.5	107.7	121.1	32.83	110.84	121.1	S. Petersen; SGW-38757	—
199-D5-124	C6388	—	N/A	—	—	—	—	—	—	N/A	—	New well location
199-D8-3	A4578	137.876	80.5	N/A	N/A	>80	N/A	>24.4	>113.5	>113.5	Williams; borehole log	Inconclusive (drill log)
199-D8-4	A4579	143.218	103.4	N/A	N/A	103.4	N/A	31.51	111.7	N/A	Williams/HWIS	Borehole and/or drillers logs
199-D8-53	A4581	132.893	69.44	NP	NP	69	NP	21.0	111.86	111.9	Williams; borehole log	Appears no Ringold Unit E
199-D8-54A	A4582	134.928	78	NP	NP	76	NP	23.2	111.76	111.8	Williams; borehole log	No Ringold Unit E
199-D8-54B	A4583	134.918	144	NP	NP	76	NP	23.2	111.75	111.8	Williams; borehole log	No Ringold Unit E
199-D8-55	A4584	135.603	75	35	10.7	69	124.9	21.0	114.57	124.9	Williams; borehole log	—
199-D8-68	B2772	134.829	80	NP	NP	75	NP	22.9	111.97	112.0	Williams; borehole log	No Ringold Unit E
199-D8-69	B2773	130.53	62	NP	NP	57.5	NP	17.5	113.00	113.0	Williams; borehole log	Ringold Unit E
199-D8-70	B2774	131.948	74	NP	NP	71	NP	21.6	110.31	110.3	Williams; borehole log	No Ringold Unit E
199-D8-71	B2775	133.717	81	NP	NP	77	NP	23.5	110.25	110.2	Williams; borehole log	No Ringold Unit E
699-100-43B	C5647	122.184	35.1	NP	NP	29.5	NP	9.0	113.2	113.2	Weekes; DOE/RL-2008-42	—
699-101-45	C5666	121.809	30.8	NP	NP	25.5	NP	7.77	114.04	114.0	Weekes; DOE/RL-2008-42	—
699-101-48c	A9102	119.415	77	NP	NP	49.0	NP	14.9	104.5	104.5	Williams; drill log review 2009	Elevation is corrected to GS (0.3-ft stickup)
699-101-48c	A9102	118.91	77	NP	NP	49.0	NP	14.9	104.0	104.0	Williams; drill log review 2009	Elevation is corrected to GS (1.1-ft stickup)
699-74-44	A5328	136.703	150	TBD	TBD	55	TBD	16.8	119.94	—	Williams; HWIS	Elevation is top casing/drill log
699-74-48	A5329	149.417	150	TBD	TBD	124	TBD	37.8	111.62	TBD	Williams; HWIS	Elevation is top casing/drill log
699-77-54	A5331	147.346	152	95	28.9	152	118.4	46.3	101.02	118.40	Williams; HWIS	Elevation is top casing/drill log

Table 3-1. 100-HR-3 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-40781, Rev. 1)

Well Number	Hanford Well ID	Ground Elev. NAVD88 (m) (Disc Z or Brass Cap)	Total Depth (ft bgs)	Top Ringold Formation Rwie (Unit E) (ft bgs)	Top Ringold Formation Rwie (Unit E) (m bgs)	Top RUM (ft bgs)	Elev. Ringold Formation Rwie (Unit E) (m amsl)	Top RUM (m bgs)	Elev. RUM (m amsl)	Elev. Hanford/Ringold Formation Contact (m amsl)	Geologist/Data Source	Comments/ Observations
699-80-43P	A8993	127.137	450	NP	NP	46	NP	14.0	113.12	113.12	Williams; HWIS	Elevation is top casing/drill log
699-83-47	A5341	133.704	152	35	10.7	95	123.0	29.0	104.75	123.0	Williams; HWIS	Elevation is top casing/drill log
699-87-47	A0969	—	N/A	Decommissioned		—	—	—	—	—	—	—
699-87-55	A5346	141.122	94	61	18.6	>94	122.5	>28.7	<112	122.5	Williams; borehole log	Inconclusive (drill log)
699-88-41	A5347	127.822		—	—	—	—	—	—	—	Williams; HWIS	—
699-88-47	A9073	—	N/A	Decommissioned		—	—	—	—	—	—	—
699-90-45	A5352	129.511	40.1	N/A	N/A	NDE	N/A	NDE	NDE	N/A	Williams; HWIS	—
699-90-45	A5352	129.511	42	NDE	NDE	NDE	NDE	NDE	<116.7	NDE	Williams; borehole log	Top of casing
699-90-47	A9076	—	N/A	Decommissioned		—	—	—	—	—	—	—
699-90-49	A9077	129.383	N/A	Decommissioned		—	—	—	—	—	—	—
699-91-46A	—	—	45.5	NDE	NDE	NDE	NDE	NDE	NDE	NDE	—	—
699-91-46A	A5354	127.255	45.5	NDE	NDE	NDE	NDE	NDE	<113.4	NDE	Williams; borehole log	—
699-91-46A	A5354	—	45.5	—	—	—	—	—	—	—	Weekes; DOE/RL-2008-42	—
699-91-48A	A9080	—	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	—	No information
699-93-48A	A5356	133.544	83	NP	NP	73	NP	22.3	111.29	111.3	Weekes; DOE/RL-2008-42	Gross grams (also listed as 699-92-49)
699-94-41	C5665	124.959	40.12	NP	NP	35.5	NP	10.8	114.1	114.1	Weekes; DOE/RL-2008-42	—
699-94-43	C5661	129.81	60.7	45	13.7	55.5	116.1	16.9	112.9	116.1	Weekes; DOE/RL-2008-42	—
699-95-45	C5660	128.536	50.4	NP	NP	45.3	NP	13.8	114.7	114.7	Weekes; DOE/RL-2008-42	—
699-95-48	C5667	130.692	64.37	NP	NP	59.0	NP	17.98	112.71	112.7	Weekes; DOE/RL-2008-42	—
699-95-51	C5663	132.292	71.3	NP	NP	66.0	NP	20.1	112.2	112.2	Weekes; DOE/RL-2008-42	—
699-95-51	C5663	132.292	71.3	59?	18.0	66	?	20.1	112.18	112.2	Williams; borehole log	Possible remnant of Ringold Unit E
699-96-43	A5357	128.714	50.8	NP	NP	45	NP	13.7	115.00	115.0	Williams; borehole log	Mistaken as 699-91-43
699-96-49	A5358	128.805	100	NP	NP	61	18.6	18.6	110.21	110.2	Williams; borehole log	Inconclusive (drill log)
699-96-52B	C5668	123.562	46	NP	NP	40.0	NP	12.19	111.37	111.4	Weekes; DOE/RL-2008-42	—
699-97-41	C5657	127.594	58.7	NP	NP	54.0	NP	16.5	111.1	111.1	Weekes; DOE/RL-2008-42	—
699-97-43B	C5664	129.344	53.4	NP	NP	48.0	NP	14.6	114.7	114.7	Weekes; DOE/RL-2008-42	—
699-97-43C	C5685	129.411	126	NP	NP	50.5	NP	15.39	114.02	114.0	Weekes; DOE/RL-2008-42	—
699-97-45	C5659	126.031	45.7	NP	NP	39.9	NP	12.2	113.9	113.9	Weekes; DOE/RL-2008-42	Adjacent to 97-45B
699-97-45B	C5686	125.986	120.4	NP	NP	39.6	NP	12.07	113.92	113.9	Weekes; DOE/RL-2008-42	Adjacent to 97-45
699-97-48B	C5662	129.018	59.22	47	14.3	54.0	114.7	16.5	112.6	114.7	Weekes; DOE/RL-2008-42	Only remnant Ringold Unit E remains
699-97-48C	C5687	129.072	123	49	14.9	55.0	114.1	16.76	112.31	114.1	Weekes; DOE/RL-2008-42	Only remnant Ringold Unit E remains

Table 3-1. 100-HR-3 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-40781, Rev. 1)

Well Number	Hanford Well ID	Ground Elev. NAVD88 (m) (Disc Z or Brass Cap)	Total Depth (ft bgs)	Top Ringold Formation Rwie (Unit E) (ft bgs)	Top Ringold Formation Rwie (Unit E) (m bgs)	Top RUM (ft bgs)	Elev. Ringold Formation Rwie (Unit E) (m amsl)	Top RUM (m bgs)	Elev. RUM (m amsl)	Elev. Hanford/Ringold Formation Contact (m amsl)	Geologist/Data Source	Comments/ Observations
699-97-51A	A5362	—	N/A	—	—	—	0.0	—	—	—	—	Drill log
699-98-43	C5656	122.435	39.5	NP	NP	34.0	NP	10.4	112.1	112.1	Weekes; DOE/RL-2008-42	—
699-98-46	C5658	127.372	45.6	NP	NP	40.5	NP	12.3	115.0	115.0	Weekes; DOE/RL-2008-42	—
699-98-51	C5669	120.402	30.1	NP	NP	25.0	NP	7.62	112.78	112.8	Weekes; DOE/RL-2008-42	—
699-99-41	C5649	125.633	45.6	NP	NP	40.0	NP	12.2	113.4	113.4	Weekes; DOE/RL-2008-42	—
699-99-42B	C5648	127.116	51.6	NP	NP	45.5	NP	13.9	113.3	113.3	Weekes; DOE/RL-2008-42	—
699-99-44	C5650	124.159	37.5	NP	NP	32.5	NP	9.9	114.3	114.3	Weekes; DOE/RL-2008-42	—
ISRM Treatment Zone Injection/Extraction Wells												
199-D3-3	C3312	143.202	114	64	19.5072	113.5	123.7	34.6	108.61	123.7	DOE/RL-2003-05, Rev. 0	—
199-D3-4	C3314	143.252	114.2	67.6	20.6045	113	122.6	—	143.25	122.6	DOE/RL-2003-05, Rev. 0	—
199-D4-68	C3298	143.067	113	60	18.288	112	124.8	34.1	108.93	124.8	DOE/RL-2003-05, Rev. 0	—
199-D4-69	C3299	143.084	111	59	17.9832	110	125.1	33.5	109.56	125.1	DOE/RL-2003-05, Rev. 0	—
199-D4-70	C3300	143.131	111	61	18.5928	110.5	124.5	33.7	109.45	124.5	DOE/RL-2003-05, Rev. 0	—
199-D4-71	C3301	143.119	111.6	60	18.288	110.5	124.8	33.7	109.44	124.8	DOE/RL-2003-05, Rev. 0	—
199-D4-72	C3302	142.998	111.9	59	17.9832	111	125.0	33.8	109.17	125.0	DOE/RL-2003-05, Rev. 0	—
199-D4-73	C3303	143.148	112	60.5	18.4404	111.5	124.7	34.0	109.16	124.7	DOE/RL-2003-05, Rev. 0	—
199-D4-74	C3304	142.901	112.5	60	18.288	111.5	124.6	34.0	108.92	124.6	DOE/RL-2003-05, Rev. 0	—
199-D4-75	C3305	143.069	114.5	59.5	18.1356	113.5	124.9	34.6	108.47	124.9	DOE/RL-2003-05, Rev. 0	—
199-D4-76	C3306	142.971	114	60.5	18.4404	112.5	124.5	34.3	108.68	124.5	DOE/RL-2003-05, Rev. 0	—
199-D4-77	C3307	142.929	111.2	60.5	18.4404	111	124.5	33.8	109.10	124.5	DOE/RL-2003-05, Rev. 0	—
199-D4-78	C3308	142.981	113	61	18.5928	112	124.4	34.1	108.84	124.4	DOE/RL-2003-05, Rev. 0	—
199-D4-79	C3309	143.627	115.1	63	19.2024	113	124.4	34.4	109.18	124.4	DOE/RL-2003-05, Rev. 0	—
199-D4-80	C3310	143.43	113	61	18.5928	112.8	124.8	34.4	109.05	124.8	DOE/RL-2003-05, Rev. 0	—
199-D4-81	C3311	143.329	112.8	61.5	18.7452	112.5	124.6	34.3	109.04	124.6	DOE/RL-2003-05, Rev. 0	—
199-D4-82	C3313	143.229	115	65	19.812	113.5	123.4	34.6	108.63	123.4	DOE/RL-2003-05, Rev. 0	—
ISRM Characterization/Small-Diameter Groundwater Monitoring Wells												
199-D4-87	C3799	143.444	100	N/A	N/A	97.2	N/A	29.6	113.82	N/A	DOE/RL-2003-05, Rev. 0	—
199-D4-88	C3800	143.399	98	60	18.288	NDE	125.1	NDE	NDE	125.1	DOE/RL-2003-05, Rev. 0	—
199-D4-89	C3801	143.529	97.5	65	19.812	97	123.7	29.6	113.96	123.7	DOE/RL-2003-05, Rev. 0	—

Table 3-1. 100-HR-3 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-40781, Rev. 1)

Well Number	Hanford Well ID	Ground Elev. NAVD88 (m) (Disc Z or Brass Cap)	Total Depth (ft bgs)	Top Ringold Formation Rwie (Unit E) (ft bgs)	Top Ringold Formation Rwie (Unit E) (m bgs)	Top RUM (ft bgs)	Elev. Ringold Formation Rwie (Unit E) (m amsl)	Top RUM (m bgs)	Elev. RUM (m amsl)	Elev. Hanford/Ringold Formation Contact (m amsl)	Geologist/Data Source	Comments/ Observations
Bio-Stimulation Project Wells (PNNL)												
199-D5-108	C5578	144.383	106	75?	22.9	103	121.5	31.4	113.0	121.5	Personal communication; PNNL to publish this data set under Truex et al.	—
199-D5-109	C5579	144.022	104.1	73	22.2	104.1	121.8	31.7	112.3	121.8	Personal communication	—
199-D5-110	C5580	144.116	102.5	68	20.7	100.5	123.4	30.6	113.5	123.4	Personal communication	—
199-D5-111	C5581	144.109	101.7	70	21.3	100	122.8	30.5	113.6	122.8	Personal communication	—
199-D5-112	C5582	143.991	93.85	68?	20.7	>93.9	123.3	28.6	<115.4	123.3	Personal communication	—
199-D5-113	C5583	143.993	102	68?	20.7	100.5	123.3	30.6	113.4	123.3	Personal communication	—
199-D5-114	C5584	144.359	104.3	73	22.2	104.3	122.1	31.8	112.6	122.1	Personal communication	—
199-D5-115	C5585	144.388	105	73	22.2	104	122.1	31.7	112.7	122.1	Personal communication	—
199-D5-116	C5586	144.423	104.5	74	22.5	104	121.9	31.7	112.7	121.9	Personal communication	—
199-D5-117	C5587	144.392	91.6	73.5	22.4	>91.6	122.0	27.9	<116.5	122.0	Personal communication	—
199-D5-118	C5588	144.373	104.5	73.5	22.4	104	122.0	31.7	112.7	122.0	Personal communication	—
199-D4-15	B8073	143.658	105	50	15.2	100	128.4	30.5	113.2	128.4	Personal communication	—
199-D4-20	B8750	143.556	107.50	63.00	19.2	105	124.4	32.0	111.6	124.4	Personal communication	—
199-D5-40	B8749	143.976	109.50	74.00	22.5	106	121.5	32.3	111.7	121.5	Personal communication	—
199-D2-6	A4568	143.355	110.70	75?	22.9	103	120.5	31.4	112.0	120.5	Personal communication	—
199-H3-1	A4610	129.130	75	NP	NP	56	NP	17.06	112.07	112.1	Drill log; PNL-6728	—
199-H3-2A	A4611	128.017	56	NP	NP	54	NP	16.45	111.56	111.6	Geo log; PNL-6728	—
199-H3-2B	A4612	128.015	58	NP	NP	57	NP	17.37	110.65	110.6	Geo log; PNL-6728	—
199-H3-2C	A4613	128.022	155	NP	NP	55	NP	16.76	111.26	111.3	Geo log; PNL-6728	—
199-H3-3	B2778	128.053	53	NP	NP	49	NP	14.93	113.12	113.1	Mehlhorn; BHI-00953	—
199-H3-4	B2779	126.461	49	NP	NP	45	NP	13.71	112.75	112.7	Mehlhorn; BHI-00953	—
199-H3-5	B2780	126.291	49	NP	NP	45.5	NP	13.86	112.43	112.4	Mehlhorn; BHI-00953	—
199-H4-1	A5685	127.484	75	NP	NP	55	NP	16.76	110.73	110.7	Drill log	Casing removed, elevation estimated
199-H4-2	A5686	128.206	386	NP	NP	59	NP	17.98	110.23	110.2	Drill log; PNL-6728	—
199-H4-3	A4629	128.476	55	NP	NP	50	NP	15.24	113.24	113.2	Drill log; PNL-6728	—
199-H4-4	A4630	126.866	55	NP	NP	NDE	NP	NDE	<110.1	<110.1	Drill log; PNL-6728	—
199-H4-5	A4636	127.326	60	NP	NP	48	NP	14.63	112.70	112.7	Drill log; PNL-6728	—
199-H4-6	A4637	128.670	55	NP	NP	NDE	NP	NDE	<112.2	<112.2	Drill log; PNL-6728	—
199-H4-7	A4638	128.755	55	NP	NP	54	NP	16.45	112.30	112.3	Geo log; PNL-6728	—

Table 3-1. 100-HR-3 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-40781, Rev. 1)

Well Number	Hanford Well ID	Ground Elev. NAVD88 (m) (Disc Z or Brass Cap)	Total Depth (ft bgs)	Top Ringold Formation Rwie (Unit E) (ft bgs)	Top Ringold Formation Rwie (Unit E) (m bgs)	Top RUM (ft bgs)	Elev. Ringold Formation Rwie (Unit E) (m amsl)	Top RUM (m bgs)	Elev. RUM (m amsl)	Elev. Hanford/Ringold Formation Contact (m amsl)	Geologist/Data Source	Comments/ Observations
199-H4-8	A4639	128.596	55	NP	NP	48	NP	14.63	113.97	114.0	Geo log; PNL-6728	—
199-H4-9	A4640	128.280	51	NP	NP	46.5	NP	14.17	114.11	114.1	Geo log; PNL-6728	—
199-H4-10	A4614	123.700	38	NP	NP	38	NP	11.58	112.12	112.1	Geo log; PNL-6728	—
199-H4-11	A4615	127.680	59	NP	NP	59	NP	17.98	109.70	109.7	Geo log; PNL-6728	—
199-H4-12A	A4616	126.470	52	NP	NP	51	NP	15.54	110.93	110.9	Geo log; PNL-6728	—
199-H4-12B	A4617	126.461	51	NP	NP	50.5	NP	15.39	111.07	111.1	Geo log; PNL-6728	—
199-H4-12C	A4618	126.342	220	NP	NP	50	NP	15.24	111.11	111.1	Geo log; PNL-6728	—
199-H4-13	A4619	127.979	61	NP	NP	59	NP	17.98	110.00	110.0	Geo log; PNL-6728	—
199-H4-14	A4620	128.614	60	NP	NP	59	NP	17.98	110.64	110.6	Geo log; PNL-6728	—
199-H4-15A	A4621	124.631	46	NP	NP	44	NP	13.41	111.22	111.2	Geo log; PNL-6728	—
199-H4-15B	A4622	124.541	44	NP	NP	43	NP	13.10	111.44	111.4	Geo log; PNL-6728	—
199-H4-15C	A5689	124.636	330	NP	NP	46	NP	14.02	110.62	110.6	Geo log; PNL-6728	—
199-H4-16	A4626	129.820	61	NP	NP	59	NP	17.98	111.84	111.8	Geo log; PNL-6728	—
199-H4-17	A4627	128.346	46.5	NP	NP	45	NP	13.71	114.63	114.6	Geo log; PNL-6728	—
199-H4-18	A4628	129.101	51	NP	NP	49	NP	14.93	114.17	114.2	Geo log; PNL-6728	—
199-H4-45	A4631	127.128	54.5	NDE	NDE	NDE	NDE	NDE	<110.5	<110.5	Lindemann; log/DOE/RL-93-43	—
199-H4-46	A4632	129.380	61.5	NP	NP	61	NP	18.59	110.79	110.8	Lindemann; log/DOE/RL-93-43	—
199-H4-47	A4633	129.554	59.9	NDE	NDE	NDE	NP	NDE	<111.3	<111.3	Lindemann; log/DOE/RL-93-43	—
199-H4-48	A4634	129.966	62	NP	NP	62	NP	18.89	111.07	111.1	Lindemann; log/DOE/RL-93-43	—
199-H4-49	A4635	129.615	60	NP	NP	56	NP	17.06	112.55	112.6	Lindemann; log/DOE/RL-93-43	—
199-H4-63	B2776	127.596	62	NP	NP	57	NP	17.37	110.23	110.2	Walker; log/BHI-00953	—
199-H4-64	B2777	125.289	54	NP	NP	46	NP	14.02	111.27	111.3	Walker; log/BHI-00953	—
199-H4-65	B8759	128.818	53	NP	NP	50	NP	15.24	113.58	113.6	Moore; log	—
199-H5-1A	A4641	128.172	57	NP	NP	52	NP	15.84	112.33	112.3	Geo log; DOE/RL-93-43	—
199-H6-1	A4642	127.552	56.2	NP	NP	NDE	NP	NDE	<110.4	<110.4	Geo log; DOE/RL-93-43	—

Table 3-1. 100-HR-3 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-40781, Rev. 1)

Well Number	Hanford Well ID	Ground Elev. NAVD88 (m) (Disc Z or Brass Cap)	Total Depth (ft bgs)	Top Ringold Formation Rwie (Unit E) (ft bgs)	Top Ringold Formation Rwie (Unit E) (m bgs)	Top RUM (ft bgs)	Elev. Ringold Formation Rwie (Unit E) (m amsl)	Top RUM (m bgs)	Elev. RUM (m amsl)	Elev. Hanford/Ringold Formation Contact (m amsl)	Geologist/Data Source	Comments/ Observations

Yellow-shaded cells indicate questionable data.

The references cited in this table are included in the reference list in Chapter 11.

amsl = above mean sea level
bgs = below ground surface
HWIS = Hanford Well Information System
ID = identification
ISRM = In Situ Redox Manipulation
N/A = not available
NAVD88 = North American Vertical Datum of 1988
NDE = not drilled deep enough
NP = not present (not encountered in subsurface)
PNNL = Pacific Northwest National Laboratory
RUM = Ringold Upper Mud (unit)
TBD = to be determined

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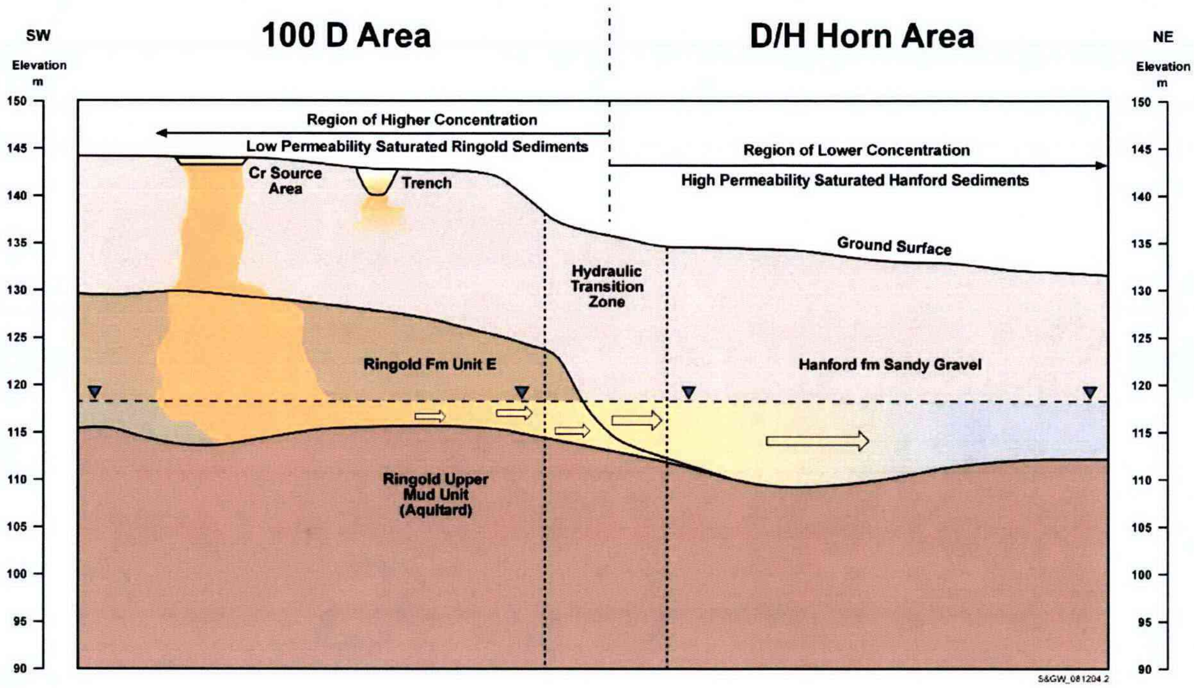
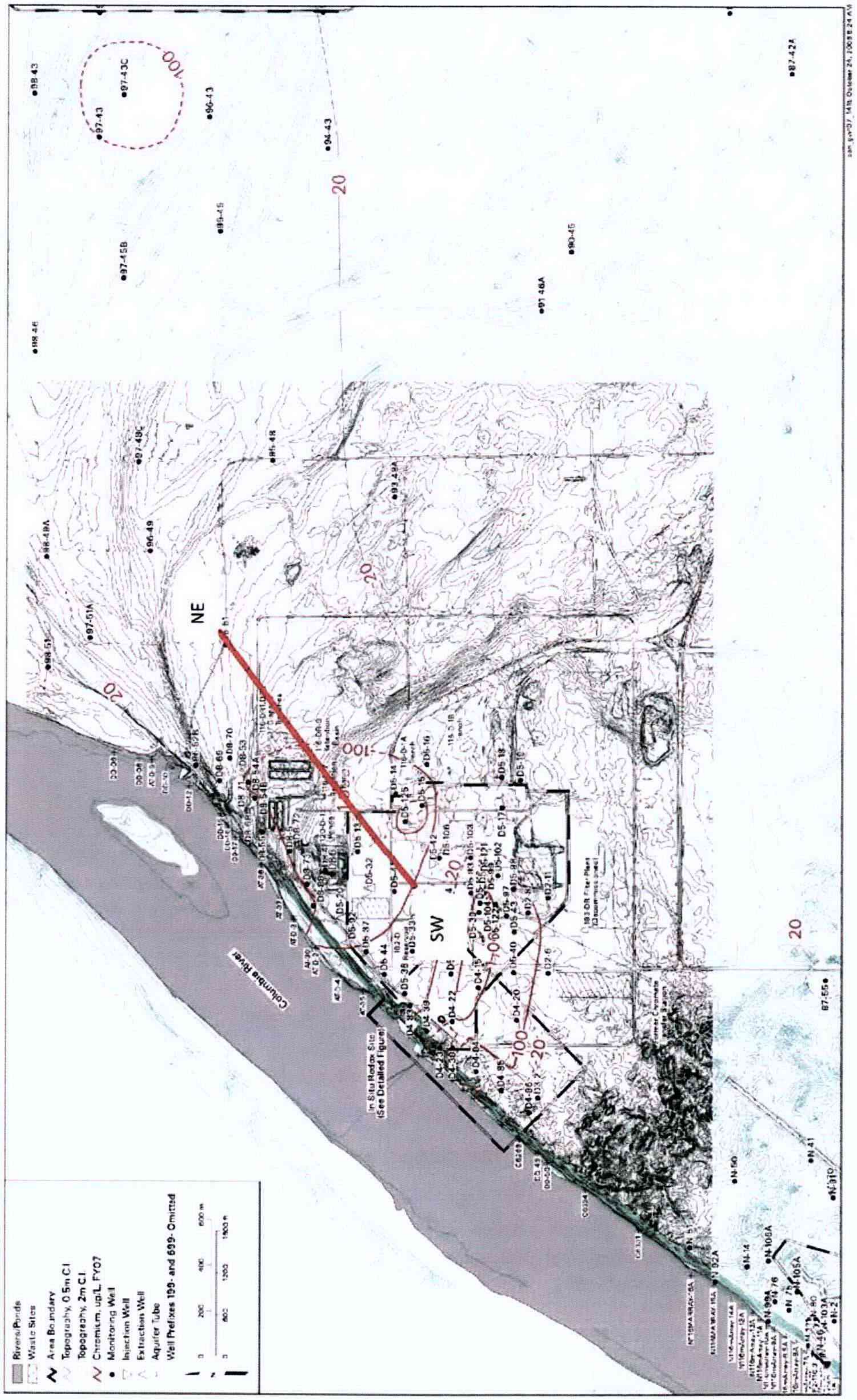


Source: SGW-40781, Rev. 1, *100-HR-3 Remedial Process Optimization Modeling Data Package.*

Figure 3-2. Conceptual Hydrogeologic Cross-Section of the 100-HR-3 Operable Unit Depicting Hypothetical Contaminant Migration Beneath Waste Sites

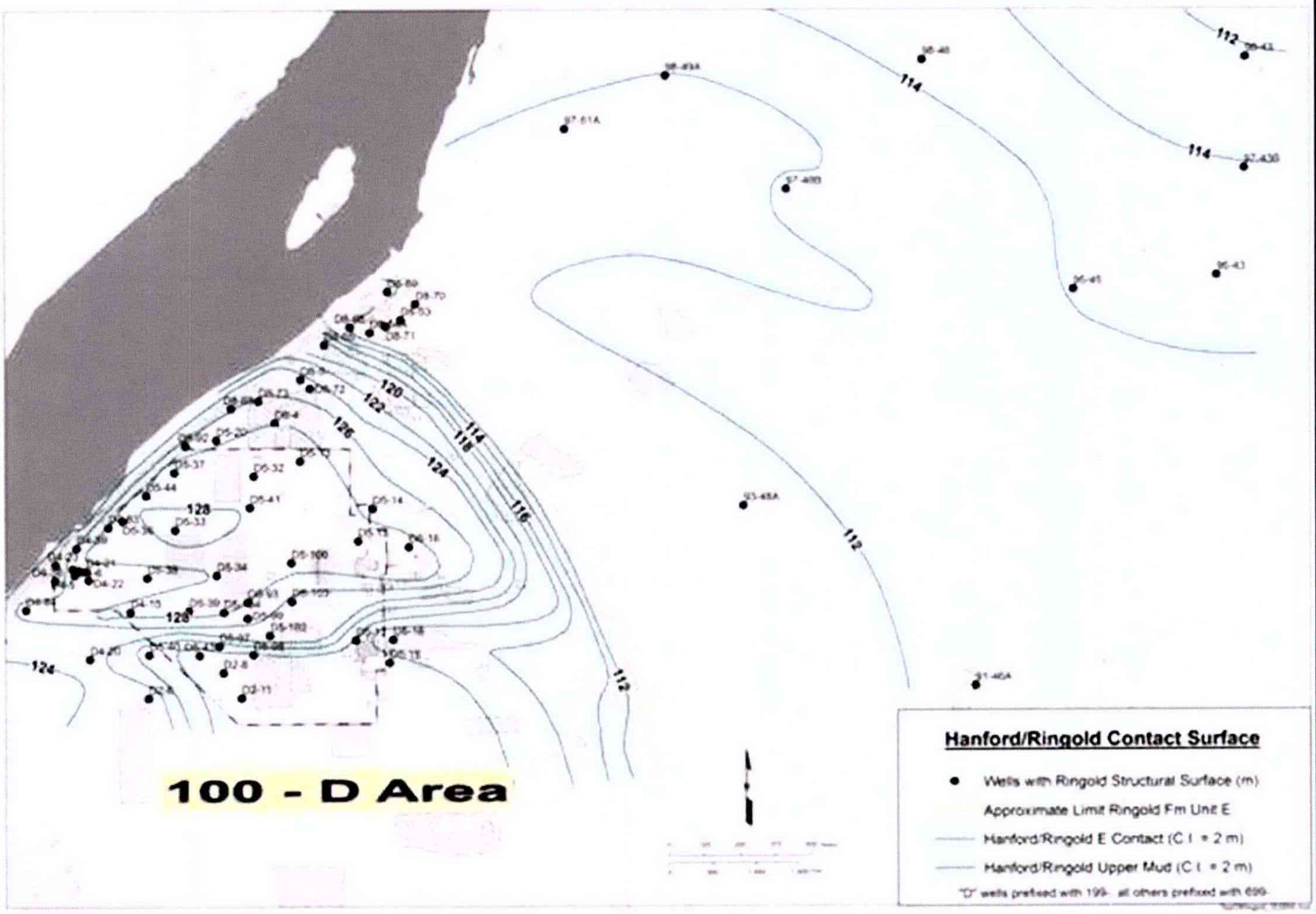
Beneath the 100-D Area, roughly coincident with the localized topographic high that covers this area, the uppermost aquifer resides in the Ringold Unit E fluvial silty-sandy gravel. The lateral extent of Ringold Unit E is defined by various data sets (as previously mentioned), and truncation of Ringold Unit E is reflected by the prominent topographic elevation drop east of the100-D Area (Figure 3-3). This topographic feature is believed to be a surface expression of the paleoflood erosional event(s) that removed most of Ringold Unit E (Figure 3-2).

From this point eastward, the aquifer flows out of Ringold Unit E (across this hydraulic boundary) and into the adjacent Hanford formation sediment directly overlying the RUM (Figure 3-2). This transition creates several changes within the aquifer. Aquifer testing and water-level data suggest that Hanford formation sediment is more permeable and exhibits more unrestricted flow properties than Ringold Unit E sediment. The data suggest that groundwater contamination disperses more rapidly within the saturated Hanford formation sediment and may be impacted more readily by fluctuations in river level, effluent disposal, etc., resulting in rapid spreading, dispersion, and dilution of contaminant concentrations.



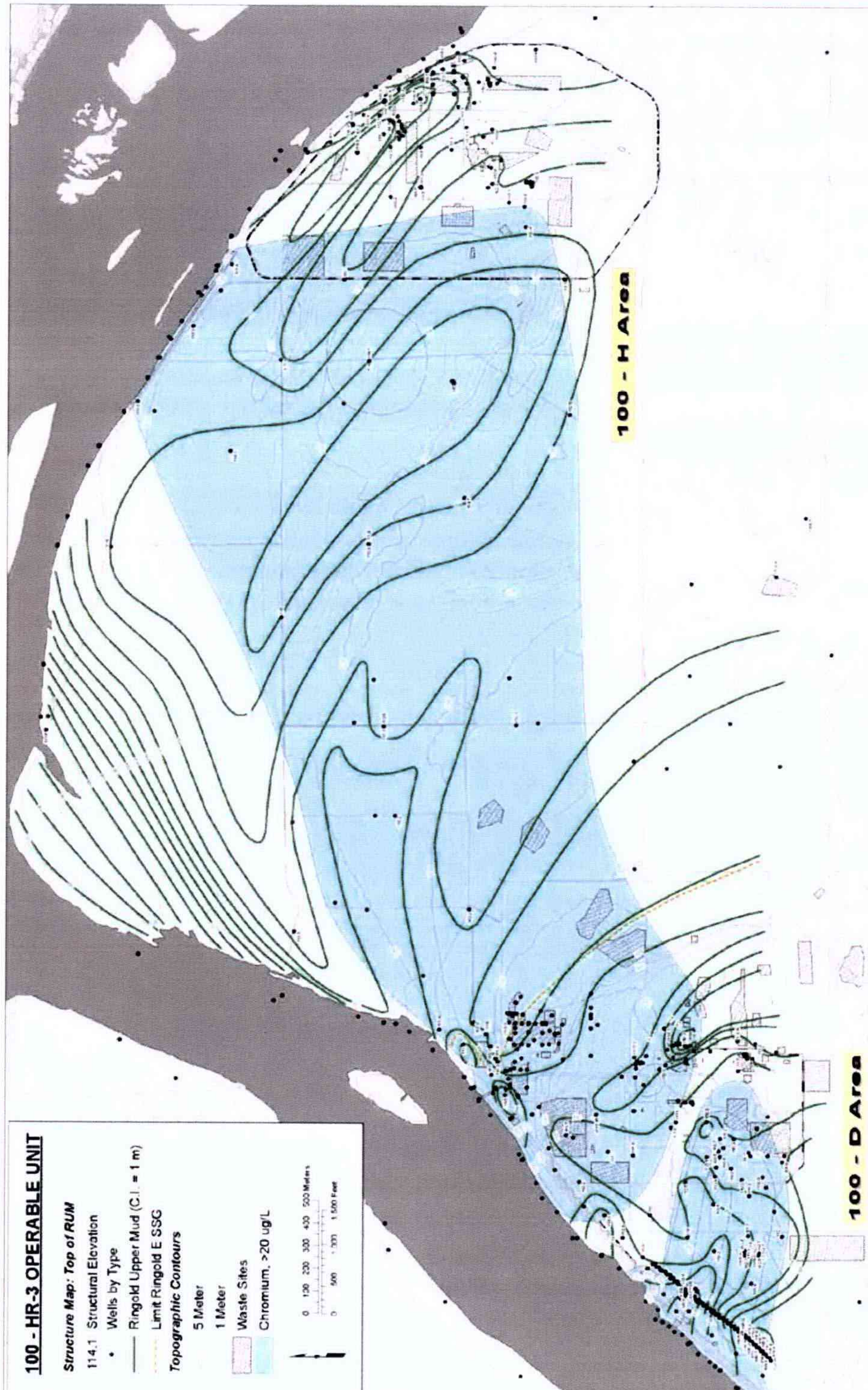
Source: SGW-40781, Rev. 1, *100-HR-3 Remedial Process Optimization Modeling Data Package*.

Figure 3-3. 100-D Area Location Map



Source: SGW-40781, Rev. 1, *100-HR-3 Remedial Process Optimization Modeling Data Package.*

Figure 3-4. Structural Contour Map of the Hanford/Ringold Contact Surface (Disconformity) Beneath the 100-HR-3 Operable Unit



Source: SGW-40781, Rev. 1, *100-HR-3 Remedial Process Optimization Modeling Data Package.*

Figure 3-5. Structural Contour Map of the Ringold Upper Mud Unit Surface for 100-HR-3 Operable Unit

3.2.2 100-KR-4 Operable Unit Hydrogeology

A detailed description of 100 Areas geology was presented in the preceding subsection in the context of 100-HR-3 OU geology. This subsection presents primarily site-specific data for the 100-KR-4 OU.

Table 3-2 includes 100-KR-4 OU well data to support construction of geologic structure contour maps and cross-sections. Figure 3-6 (cross-section AA') illustrates the 100-KR-4 OU stratigraphic units beneath the uppermost unconfined aquifer; the cross-section AA' runs parallel to the Columbia River. Figures 3-7, 3-8, and 3-9 (cross-sections BB', CC' and JJ', respectively) illustrate projections of the stratigraphic units perpendicular to the Columbia River. In the 100-KR-4 OU, the Hanford/ Ringold contact is predominantly above the water table (Figures 3-6 through 3-9). However, where the contact surface (disconformity) between the overlying Hanford formation and underlying Ringold Formation occurs below the river level (approximately 120 m [394 ft] average elevation) and/or the water table, it can form a preferential hydrogeologic flow path. Revised maps of the Ringold Unit E surface (the Hanford/Ringold contact) (Figure 3-10) indicate that locally, the Hanford/ Ringold contact surface is higher to the southwest, beneath the KE and KW Reactors (elevation approximately 135 to 130 m [443 to 427 ft]) and drops approximately 5 to 10 m (16 to 33 ft) to the northeast. Immediately adjacent to the Columbia River, the Hanford/Ringold contact drops in elevation more abruptly along the entire 100-KR-4 OU reach, indicating fluvial-related erosional influences of the Columbia River. There are two generally low Hanford/Ringold contact areas, both adjacent to the Columbia River, at an elevation near the average river stage. Both of these low areas may be creating a more permeable or preferential groundwater flow path that may influence the effectiveness of the pump-and-treat system to move chromium contamination located within the deeper and lower permeability Ringold Formation sediment.

Beneath the Hanford formation, the Ringold Formation sediment consists of the semi-indurated, fluvial silty sandy gravel of Ringold Unit E, which overlies the RUM's thick sequence of silt and clay (low-energy deposits) (Figure 3-1). The uppermost unconfined aquifer is contained predominantly within the Ringold Unit E sediment and is confined at the bottom of Unit E by the low-permeability RUM. The top of the RUM (Figure 3-11) ranges in elevation between approximately 86.4 to 113 m (284 to 370.8 ft) (NAVD88). However, two areas of the RUM surface may be influencing the ability to effectively pump-and-treat chromium-contaminated groundwater in the 100-KR-4 OU:

Firstly, new wells drilled in the area (e.g., 199-K-156 and 199-K-162) west of the injection well gallery and near the Columbia River, indicate a surface low in the RUM that is almost 15 m (49 ft) lower than the RUM surface beneath the injection gallery (Figures 3-7 and 3-11). This RUM low area is also coincident with the overlying low Hanford/Ringold contact surface and is in the area of persistently higher chromium concentrations. Data from the wells and aquifer tubes in this area monitoring the deeper portion of the aquifer indicate higher concentrations of chromium than surrounding shallower intervals. The injection gallery (e.g., wells 199-K-121A, 199-K-122A, 199-K-124, and 199-K-128) is screened in the shallower and dramatically thinner portion of the unconfined aquifer (Figure 3-7) and may not be effectively targeting this deeper pocket of contaminated groundwater. The occurrence of the Hanford/Ringold contact near the water table above this RUM low also tends to direct more groundwater movement preferentially into the shallower portion of the aquifer that resides in the Hanford sediments, possibly bypassing the deeper, lower permeability, contaminated Ringold Unit E groundwater (Figure 3-10).

The second contaminated area that may be influenced by the RUM surface is located to the northeast, along the 116-K-2 Trench, coincident with the higher chromium contaminated region (e.g., wells 199-K-112A, 199-K-114A, and 199-K-146) (Figure 3-11). In this region, the RUM surface is the highest near the Columbia River and forms a ridge of low-permeability sediment that is 3 to 5 m (10 to16 ft) higher than the region that is contaminated. Adjacent to this RUM ridge and slightly closer to the injection gallery is an area where the Hanford/Ringold contact surface is very near (or at) the water table and/or average Columbia River level (Figure 3-9). This is also reflected in the 2008 water table map, which illustrates a water table low at this location (DOE/RL-2008-66, *Hanford Site Groundwater Monitoring for Fiscal Year 2008*). This combination of hydrogeologic features may be causing injection water to be diverted or short circuited away from the contaminated area, thus reducing the ability to pump-and-treat the contaminated area.

3.2.3 100-BC-5 Operable Unit Hydrogeology

Table 3-3 details the 100-BC-5 OU well data supporting structure maps and cross-sections. Figure 3-12 shows the location of the geologic cross-section included in Figure 3-13. Figures 3-14 and 3-15 illustrate the Hanford/Ringold contact and RUM elevations, respectively, for the 100-BC-5 OU.

Backfill and Holocene (Recent) Deposits

Recent backfill sand and gravel and/or Holocene deposits consisting of Columbia River deposits and eolian loess, silt, sand, and gravel form surficial deposits across the 100-BC-5 OU (Figure 3-1). Due to the anthropogenic activities associated with construction of the reactors and supporting facilities, the Holocene deposits may have been removed or altered. Outside of those areas, the Holocene deposits are relatively thin, ranging up to about 2 m (6.5 ft) in thickness. Construction backfill is located near manmade structures and varies in depth, depending on the excavated depth of waste sites and building foundations. Additionally, backfill material may cover spatially larger graded areas to a depth of up to 0.3 m (1 ft).

Hanford Formation

As noted earlier, the Hanford formation consists of boulders, gravel, sand, and silt deposited by cataclysmic Ice Age floodwaters (Figure 3-1) during the Pleistocene epoch (DOE/RW-0164, *Site Characterization Plan, Reference Repository Location, Hanford Site, Washington*, Vol. 1); and is divided into gravel-dominated, sand-dominated, and interbedded sand- to silt-dominated lithofacies. While all three facies are present in the 100-BC-5 OU, the gravel-dominated sequence is the most prolific beneath the 100-BC-5 OU, likely due to its proximal location to the main paleo-flood pathway into the upper Pasco Basin from the northwest. The silt-dominated facies is not significant in the 100-BC-5 OU.
The thickness of the Hanford formation ranges from approximately 4 m (13 ft) near the Columbia River to 61 m (200 ft) in well 199-B5-8, southeast of the 100-B/C Area (Figures 3-12 and 3-13).

Table 3-2. 100-KR-4 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-41213, Rev. 0)

Well Name	Well ID	TD (ft)	Easting	Northing	Elevation (m)	Elevation (ft)	Elevation Reference	Well Type	Status	Depth to RUM (ft) (DOE/RL-2006-75)	Depth to RUM (ft)	Geologist Top of RUM Pick	Elevation of RUM (ft)	Elevation of RUM (m)	Elevation of Top of Screen (m)	Screen Length (m)	Elevation of Ringold Unit E (m)	Elevation of Bottom of Hole (m)
199-K-106A	A9842	190	568,697.40	146,502.39	142.55	467.68	HWIS, Disc_Z	Groundwater well	In use	---	162.5	Monty Mehlhorn	305.18	93.02	121.19	6.41	135.84	84.64
199-K-108A	A9844	93.5	568,687.20	146,396.14	142.77	468.42	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			121.64	6.29	133.63	114.28
199-K-107A	A9843	95.2	568,579.94	146,468.81	142.63	467.95	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			120.80	6.31	136.84	113.61
199-K-109A	A9828	165.7	569,122.18	146,748.50	142.81	468.53	HWIS, Disc_Z	Groundwater well	Decommissioned	---	155.0	Clint Degenhart	313.53	95.56	121.59	6.16	131.07	92.30
199-K-11	A4643	170	568,938.00	146,617.76	142.02	465.94	HWIS, As-Built	Groundwater well	In use	---	165.0	Mike Caron	300.94	91.73	120.99	27.74	128.30	90.20
199-K-110A	A9829	93.1	569,230.01	146,677.91	142.97	469.05	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			122.04	6.42	130.80	114.59
199-K-111A	A9830	185	569,308.17	146,968.88	140.97	462.51	HWIS, Disc_Z	Groundwater well	In use	155	155.3	Ed Rafuse	307.21	93.64	121.26	6.20	133.05	84.58
199-K-112A	B2799	54	570,278.60	148,503.44	126.49	415.00	HWIS, Disc_Z	Groundwater well	In use	48	48.0	Monty Mehlhorn	367.00	111.86	120.18	7.64	122.84	110.03
199-K-113A	B2800	48	570,098.07	148,294.45	125.94	413.18	HWIS, Disc_Z	Groundwater well	In use	41	41.0	Mike Caron	372.18	113.44	119.85	6.11	119.23	111.31
199-K-114A	B2801	51	570,020.30	148,280.55	125.73	412.49	HWIS, Disc_Z	Groundwater well	In use	41	41.0	Monty Mehlhorn	371.49	113.23	119.32	4.59	118.41	110.18
199-K-115A	B2802	61	569,939.99	148,135.42	126.58	415.28	HWIS, Disc_Z	Groundwater well	In use	54	54.0	Monty Mehlhorn	361.28	110.12	120.22	9.16	121.70	107.98
199-K-116A	B2803	92	569,871.15	147,960.50	129.94	426.32	HWIS, Disc_Z	Groundwater well	In use	87	87.0	Monty Mehlhorn	339.32	103.42	120.53	16.83	118.36	101.90
199-K-117A	B2804	73	569,702.56	147,976.98	127.08	416.92	HWIS, Disc_Z	Groundwater well	In use	68	68.0	Monty Mehlhorn	348.92	106.35	118.54	12.19	122.81	104.83
199-K-118A	B2805	81	569,703.06	147,865.90	130.06	426.72	HWIS, Disc_Z	Groundwater well	In use	76	75.5	Mike Caron	351.22	107.05	120.37	12.28	124.27	105.38
199-K-119A	B2806	92	569,661.80	147,649.69	132.57	434.93	HWIS, Disc_Z	Groundwater well	In use	89	89.0	Dave Weekes	345.93	105.44	121.47	15.24	127.69	104.53
199-K-120A	B2807	101	569,399.62	147,518.48	125.21	410.79	HWIS, Disc_Z	Groundwater well	In use	96	96.0	Monty Mehlhorn	314.79	95.95	119.42	22.86	124.29	94.42
199-K-121A	B2808	98	570,017.17	147,418.26	142.15	466.37	HWIS, Disc_Z	Groundwater well	In use	96	96.0	Monty Mehlhorn	370.37	112.89	123.74	9.16	125.69	112.28
199-K-122A	B2809	101	569,975.07	147,172.86	142.43	467.29	HWIS, Disc_Z	Unclassified	In use	100	100.0	Mike Caron	367.29	111.95	122.62	9.14	130.54	111.65
199-K-123A	B2810	98	569,931.10	147,090.24	142.84	468.64	HWIS, Disc_Z	Unclassified	In use	NR	NR	NR			124.56	9.17	131.26	112.97

Table 3-2. 100-KR-4 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-41213, Rev. 0)

Well Name	Well ID	TD (ft)	Easting	Northing	Elevation (m)	Elevation (ft)	Elevation Reference	Well Type	Status	Depth to RUM (ft) (DOE/RL-2006-75)	Depth to RUM (ft)	Geologist Top of RUM Pick	Elevation of RUM (ft)	Elevation of RUM (m)	Elevation of Top of Screen (m)	Screen Length (m)	Elevation of Ringold Unit E (m)	Elevation of Bottom of Hole (m)
199-K-124A	B2811	100	569,867.94	146,991.67	143.02	469.22	HWIS, Disc_Z	Unclassified	In use	NR	NR	NR			125.71	6.10	123.21	112.54
199-K-125A	B8559	78	569,712.87	147,866.01	130.17	427.08	HWIS, Disc_Z	Unclassified	In use	75	75	Les Walker	352.08	107.31	120.42	12.19	121.33	106.40
199-K-126	B8760	90	570,574.73	148,509.65	139.73	458.42	HWIS, Disc_Z	Groundwater well	In use	NR	NR	NR			120.09	6.10	123.88	112.29
199-K-127	C3662	115	569,539.23	147,539.00	132.17	433.63	HWIS, Disc_Z	Groundwater well	In use	NR	NR	NR			119.76	3.05	127.60	97.12
199-K-128	C3663	93.4	570,009.54	147,257.52	143.60	471.13	HWIS, Disc_Z	Groundwater well	In use	NR	98	Catherine Trice	373.13	113.73	126.74	10.68	129.88	115.13
199-K-129	C4117	51	570,283.65	148,503.07	126.59	415.33	HWIS, Disc_Z	Groundwater well	In use	48	48.0	Jess Hocking	367.33	111.96	120.04	7.62	123.54	111.05
199-K-130	C4120	80	570,478.99	148,661.18	133.66	438.50	HWIS, Disc_Z	Groundwater well	In use	NR	NR	NR			119.67	9.17	125.12	109.27
199-K-132	C4670	88	568,495.12	146,670.82	135.96	446.05	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			120.71	1.52	127.73	109.13
199-K-133	C4734	99	570,560.09	148,536.26	139.54	457.81	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			120.31	9.33	123.99	109.36
199-K-134	C4735	99	570,600.09	148,525.30	140.17	459.86	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			120.47	9.10	121.88	109.99
199-K-135	C4736	114	570,589.30	148,484.10	140.09	459.61	HWIS, Disc_Z	Groundwater well	In use	---	113.4	Jeff Weiss	346.21	105.53	120.45	9.17	124.85	105.34
199-K-136	C4737	104	570,549.02	148,494.98	139.74	458.45	HWIS, Disc_Z	Unclassified	In use	---	NR	NR			120.24	9.16	124.50	108.04
199-K-137	C5112	108.5	568,653.37	146,374.51	142.40	467.20	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			127.16	15.24	135.39	109.33
199-K-138	C5113	98.0	568,395.22	146,616.64	134.22	440.36	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			119.47	10.67	125.08	104.35
199-K-139	C5114	108.4	568,551.39	146,518.41	142.81	468.53	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			123.42	10.67	135.49	109.77
199-K-140	C5115	108	568,493.07	146,493.66	142.56	467.71	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			123.36	10.67	130.37	109.64
199-K-141	C5303	113.8	569,024.22	146,818.49	141.57	464.48	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			119.32	10.67	130.90	106.89
199-K-142	C5304	115.7	569,104.26	146,870.94	141.79	465.19	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			119.85	8.53	130.21	106.53
199-K-143	C5305	95.0	570,934.40	148,088.30	135.74	445.35	HWIS, Disc_Z	Unclassified	In use	NR	NR	NR			119.53	10.67	120.50	106.79
199-K-144	C5360	107.1	569,163.34	147,265.96	126.40	414.70	HWIS, Disc_Z	Groundwater well	In use	---	97.0	Brett Mayhew	317.70	96.83	120.52	22.86	123.05	93.76

Table 3-2. 100-KR-4 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-41213, Rev. 0)

Well Name	Well ID	TD (ft)	Easting	Northing	Elevation (m)	Elevation (ft)	Elevation Reference	Well Type	Status	Depth to RUM (ft) (DOE/RL-2006-75)	Depth to RUM (ft)	Geologist Top of RUM Pick	Elevation of RUM (ft)	Elevation of RUM (m)	Elevation of Top of Screen (m)	Screen Length (m)	Elevation of Ringold Unit E (m)	Elevation of Bottom of Hole (m)
199-K-145	C5361	123.7	569,284.60	147,425.66	125.51	411.77	HWIS, Disc_Z	Groundwater well	In use	---	118.0	Brett Mayhew	293.77	89.54	120.02	30.48	124.29	87.80
199-K-146	C5362	57.9	570,197.60	148,379.78	128.42	421.32	HWIS, Disc_Z	Groundwater well	In use	---	53.0	John Houck	368.32	112.26	119.88	7.62	123.24	110.77
199-K-147	C5363	84.1	570,411.64	148,558.07	135.07	443.13	HWIS, Disc_Z	Groundwater well	In use	---	79.0	John Houck	364.13	110.99	117.39	6.10	126.84	109.43
199-K-148	C5364	108.8	570,584.74	148,767.86	138.12	453.13	HWIS, Disc_Z	Groundwater well	In use	---	100.0	Patrick Cabbage/ Erica Rincon	353.13	107.64	119.83	12.19	122.88	104.95
199-K-152	C5368	118.6	570,736.25	148,585.89	140.25	460.12	HWIS, Disc_Z	Groundwater well	In use	---	116.0	Erika Rincon/Brett Mayhew	344.12	104.89	128.21	22.86	126.53	104.10
199-K-153	C5369	104.6	570,530.04	148,210.08	137.41	450.82	HWIS, Disc_Z	Groundwater well	In use	---	100.0	Patrick Cabbage/ Erica Rincon	350.82	106.93	128.27	21.34	125.22	105.53
199-K-154	C5370	107.9	570,320.69	148,027.72	137.09	449.77	HWIS, Vertical_Ground	Groundwater well	In use	---	102.0	Brett Mayhew	347.77	106.00	124.29	18.29	124.90	104.20
199-K-155	C5371	32.6	570,230.01	147,950.01	137.84	452.23	HWIS, Vertical_Ground	Groundwater well	Decommissioned	---	NR	NR			0.00	0.00		127.90
199-K-156	C5372	172.2	569,674.01	147,270.91	140.48	460.89	HWIS, Disc_Z	Groundwater well	In use	---	166.0	Brett Mayhew	294.89	89.88	130.12	39.62	131.34	87.99
199-K-157	C5373	143.3	569,432.18	147,167.94	138.84	455.50	HWIS, Disc_Z	Groundwater well	In use	---	139.0	Patrick Cabbage	316.50	96.47	127.13	30.48	129.69	95.16
199-K-158	C5484	115.5	568,630.54	146,163.43	145.50	477.37	HWIS, Disc_Z	Unclassified	In use	---	NR	NR			126.57	13.72	133.31	110.30
199-K-10	A5738	171.0	568,912.76	146,628.10	142.63	467.96	HWIS, as-built	Groundwater well	Decommissioned	---	164.0	Jess Hocking	303.96	92.65	95.39	3.05	128.92	90.51
199-K-13	A4644	159.0	569,037.73	146,682.13	141.03	462.70	HWIS, as-built	Groundwater well	In use	---		Jess Hocking			0.00	0.00	128.87	92.57
199-K-18	A4647	60.0	569,353.69	147,400.81	124.11	407.19	HWIS, as-built	Groundwater well	In use	NR	118.0	Jess Hocking	289.19	88.14	0.00	0.00	122.89	105.82
199-K-19	A4648	51.0	569,458.52	147,386.64	128.08	420.21	HWIS, as-built	Groundwater well	In use	NR	118.0	Jess Hocking	302.21	92.11	120.16	6.10	126.86	112.54
199-K-20	A4649	50.0	569,520.52	147,687.24	128.17	420.51	HWIS, as-built	Groundwater well	In use	NR	89.0	Jess Hocking	331.51	101.04	125.12	12.19	123.29	112.93
199-K-21	A4650	50.0	569,769.90	147,932.06	128.05	420.10	HWIS, as-built	Groundwater well	In use	NR	68.0	Jess Hocking	352.10	107.32	125.00	12.19	123.78	112.81

Table 3-2. 100-KR-4 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-41213, Rev. 0)

Well Name	Well ID	TD (ft)	Easting	Northing	Elevation (m)	Elevation (ft)	Elevation Reference	Well Type	Status	Depth to RUM (ft) (DOE/RL-2006-75)	Depth to RUM (ft)	Geologist Top of RUM Pick	Elevation of RUM (ft)	Elevation of RUM (m)	Elevation of Top of Screen (m)	Screen Length (m)	Elevation of Ringold Unit E (m)	Elevation of Bottom of Hole (m)
199-K-22	A4651	50.0	570,023.70	148,097.38	128.53	421.70	HWIS, as-built	Groundwater well	In use	NR	54.0	Jess Hocking	367.70	112.08	125.49	12.19	123.66	113.29
199-K-23	A4652	80.0	569,081.85	146,635.80	122.93	403.30	HWIS, as-built	Groundwater well	In use	---	NR	NR			103.11	4.57	110.76	98.54
199-K-25	A5743	76.0	569,140.42	147,238.15	143.26	470.00	HWIS, as-built, estimated assuming 3-ft stickup	Groundwater well	In use	---	97.0				128.02	7.62	139.90	120.09
199-K-27	A4653	90.0	569,155.96	146,763.80	141.06	462.80	HWIS, as-built	Groundwater well	Decommissioned	---	155.0	Jess Hocking	307.80	93.82	121.25	6.10	129.33	113.63
199-K-28	A4654	90.0	569,171.71	146,772.77	143.06	469.36	HWIS, as-built calculation	Groundwater well	Decommissioned	---	NR	NR			123.86	7.62	130.90	115.63
199-K-29	A5480	90.0	569,205.08	146,790.13	140.76	461.80	HWIS, as-built	Groundwater well	In use	---	NR	NR			120.94	6.10	128.60	113.32
199-K-30	A4655	90.0	569,238.12	146,780.96	140.94	462.40	HWIS, as-built	Groundwater well	In use	---	NR	NR			121.13	6.10	128.78	113.51
199-K-32A	A4657	69.0	569,024.15	147,006.68	135.47	444.45	HWIS, Disc_Z	Groundwater well	In use	NR	NR	NR			121.84	6.10	125.72	114.44
199-K-32B	A4658	176.0	569,012.40	147,004.81	135.84	445.67	HWIS, Disc_Z	Groundwater well	In use	136	136.0	T.H. Richards	309.67	94.39	87.83	3.05	124.87	82.19
199-K-33	A4659	66.6	568,573.65	146,713.25	135.33	443.99	HWIS, Disc_Z	Groundwater well	Decommissioned	---	NR	NR			121.37	6.10	127.71	115.03
199-K-34	A4660	90.6	568,605.78	146,501.94	142.75	468.34	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			122.63	5.79	136.04	115.13
199-K-35	A4661	117.0	568,832.33	146,110.68	150.84	494.88	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			123.83	6.10	137.12	115.18
199-K-36	A4662	113.0	569,373.80	146,390.73	150.79	494.71	HWIS, Disc_Z	Groundwater well	In use	---	NR	NR			123.66	6.10	131.89	116.35
199-K-37	A4663	69.3	570,216.20	148,226.54	134.76	442.13	HWIS, Disc_Z	Groundwater well	In use	NR	NR	NR			121.56	6.10	125.46	113.64
199-K-161	C5939	56.5	570,004.43	148,202.13	125.83	412.83	HWIS, Vertical_Ground	Groundwater well	In use	---	51.0	Brett Mayhew	361.83	110.29	118.67	7.62	117.30	108.61
199-K-162	C5940	133.6	569,340.00	147,459.97	125.42	411.48	HWIS, Disc_Z	Groundwater well	In use	---	128.0	Patrick Cabbage	283.48	86.41	120.12	33.53	122.37	84.70
199-K-163	C6172	113.7	570,230.66	147,947.93	137.95	452.58	HWIS, Disc_Z	Groundwater well	In use	---	110.0	Brett Mayhew	342.58	104.42	126.76	21.34	125.75	103.29
199-K-165	C6451	180.2	568,674.96	146,342.42	145.46	477.23	HWIS, Disc_Z	Groundwater well	In use	---	176.0	Betsy Woodward	301.23	91.81	128.39	33.53	136.68	90.53

Table 3-2. 100-KR-4 Operable Unit Well Data Supporting Structure Maps and Cross-Section (after SGW-41213, Rev. 0)

Well Name	Well ID	TD (ft)	Easting	Northing	Elevation (m)	Elevation (ft)	Elevation Reference	Well Type	Status	Depth to RUM (ft) (DOE/RL-2006-75)	Depth to RUM (ft)	Geologist Top of RUM Pick	Elevation of RUM (ft)	Elevation of RUM (m)	Elevation of Top of Screen (m)	Screen Length (m)	Elevation of Ringold Unit E (m)	Elevation of Bottom of Hole (m)
199-K-166	C6452	170.65	568,594.56	146,342.97	144.54	474.22	HWIS, Disc_Z	Groundwater well	In use	---	168.3	Betsy Woodward	305.97	93.26	124.43	30.48	136.34	92.53
199-K-167	C6453	37.0	568,675.81	146,267.56	145.47	477.26	HWIS, Vertical_Brass	Groundwater well	Decommissioned	---	NR	NR			0.00	0.00	134.80	134.19
199-K-168	C6454	166.8	568,544.37	146,513.63	142.59	467.83	HWIS, Disc_Z	Groundwater well	In use	---	160.0	Kim Royal	307.83	93.83	111.91	18.22	134.88	91.75
199-K-169	C6744	142.0	569,988.97	147,554.98	141.86	465.43	HWIS, Disc_Z	Groundwater well	In use	---	132.0	Betsy Woodward	333.43	101.63	132.11	30.48	128.15	98.58
199-K-170	C6745	151.0	570,009.01	147,491.37	141.87	465.45	HWIS, as-built calculation	Groundwater well	In use	---	149.0	Betsy Woodward	316.45	96.45	134.86	36.58	128.15	95.84
199-K-171	C6746	153.6	570,544.03	147,187.86	144.22	473.17	HWIS, Disc_Z	Groundwater well	In use	---	148.0	Betsy Woodward	325.17	99.11	135.69	36.58	125.93	97.40
199-K-172	C6747	140.0	570,871.69	147,166.37	144.26	473.28	HWIS, Disc_Z	Groundwater well	In use	---	132.0	Betsy Woodward	341.28	104.02	134.50	30.48	125.97	101.59
199-K-173	C7016	181.0	568,674.07	146,266.88	145.63	477.78	HWIS, Disc_Z	Groundwater well	In use	---	174.5	Betsy Woodward	303.28	92.44	126.42	18.29	130.39	90.46
199-K-7	A5735	42.0	569,298.47	147,427.46	123.89	406.47	HWIS, vertical estimated assuming 3 ft stickup	Unclassified	Decommissioned	---					0.00	0.00		111.09
699-73-61	A5327	150.0	571,420.82	145,781.53	161.48	529.80	HWIS, as-built	Groundwater well	In use	---	155.0	Jess Hocking	374.80	114.24	128.87	11.89		115.76
699-78-62	A5332	150.0	570,877.30	147,166.22	142.65	468.00	HWIS, as-built	Groundwater well	In use	120	125.0	Jess Hocking	343.00	104.55	0.00	0.00	124.36	96.93
699-81-62	A9000	1011.0	570,943.03	148,103.09	134.112	440.00	HWIS, as-built	Groundwater well	In use	---		Bruce Williams	?	103.33	0.00	0.00	118.87	-174.04
699-81-64B	A9002	38.0	570,385.80	148,163.80	137.41	450.82	Estimated to be same or similar to 199-K-153	Unclassified	Decommissioned	---	100.0	Jess Hocking	350.82	106.93	0.00	0.00	125.22	125.83

DOE/RL-2006-75, *Supplement to the 100-HR-3 and 100-KR-4 Remedial Design Report and Remedial Action Workplan for the Expansion of the 100-KR-4 Pump and Treat System.*

HWIS = Hanford Well Information System

ID = identification

NR = not reached

RUM = Ringold Upper Mud (unit)

TD = total depth

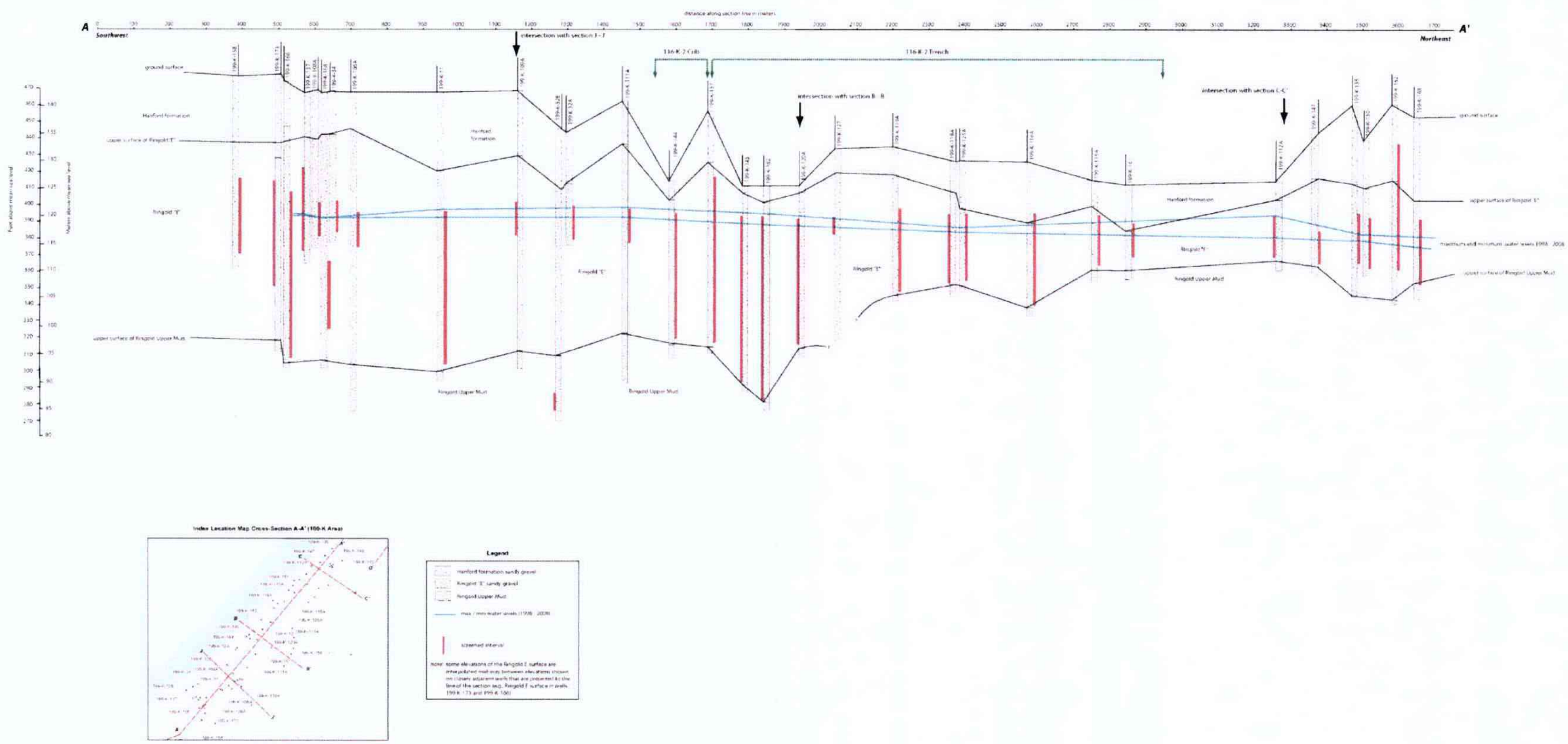


Figure 3-6. Cross-Section AA' of the 100-KR-4 Operable Unit Depicting Hydrogeologic Units Comprising the Uppermost Unconfined Aquifer (after SGW-41213, Rev. 0)

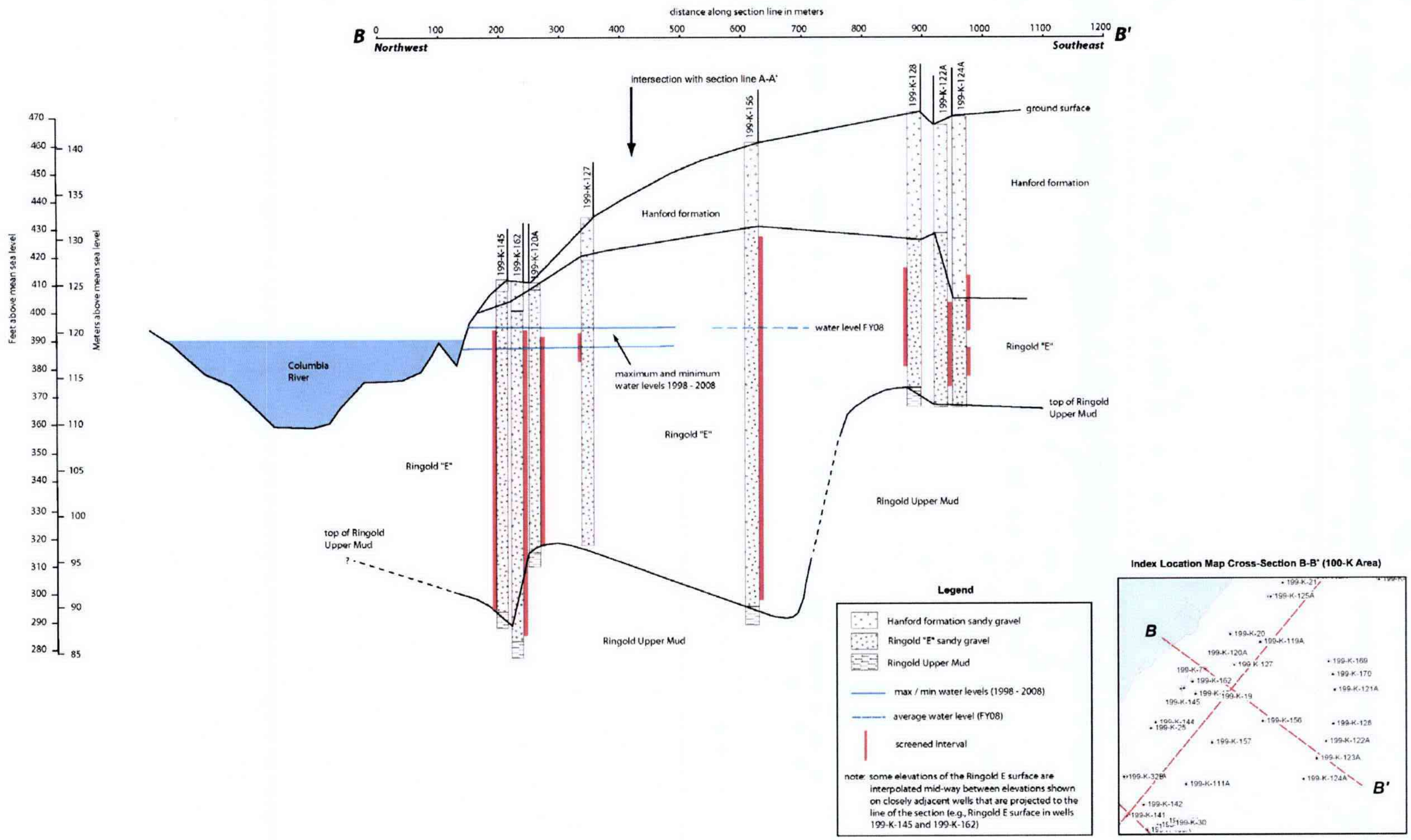


Figure 3-7. Cross-Section BB' Depicting Hydrogeologic Unit Projections into the Columbia River, 100-KR-4 Operable Unit (after SGW-41213, Rev. 0)

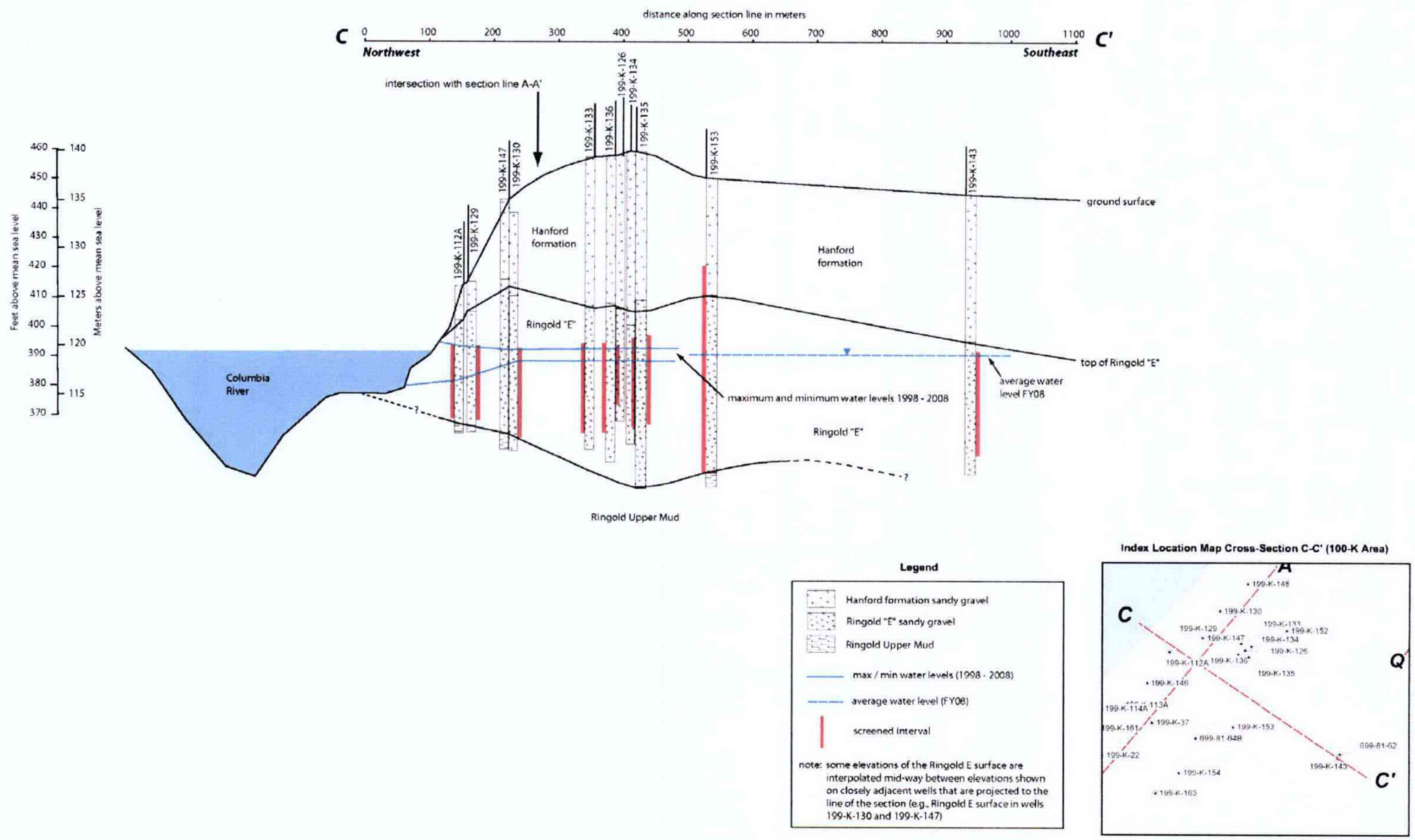


Figure 3-8. Cross-Section CC' Depicting Hydrogeologic Unit Projections into the Columbia River, 100-KR-4 Operable Unit (after SGW-41213, Rev. 0)

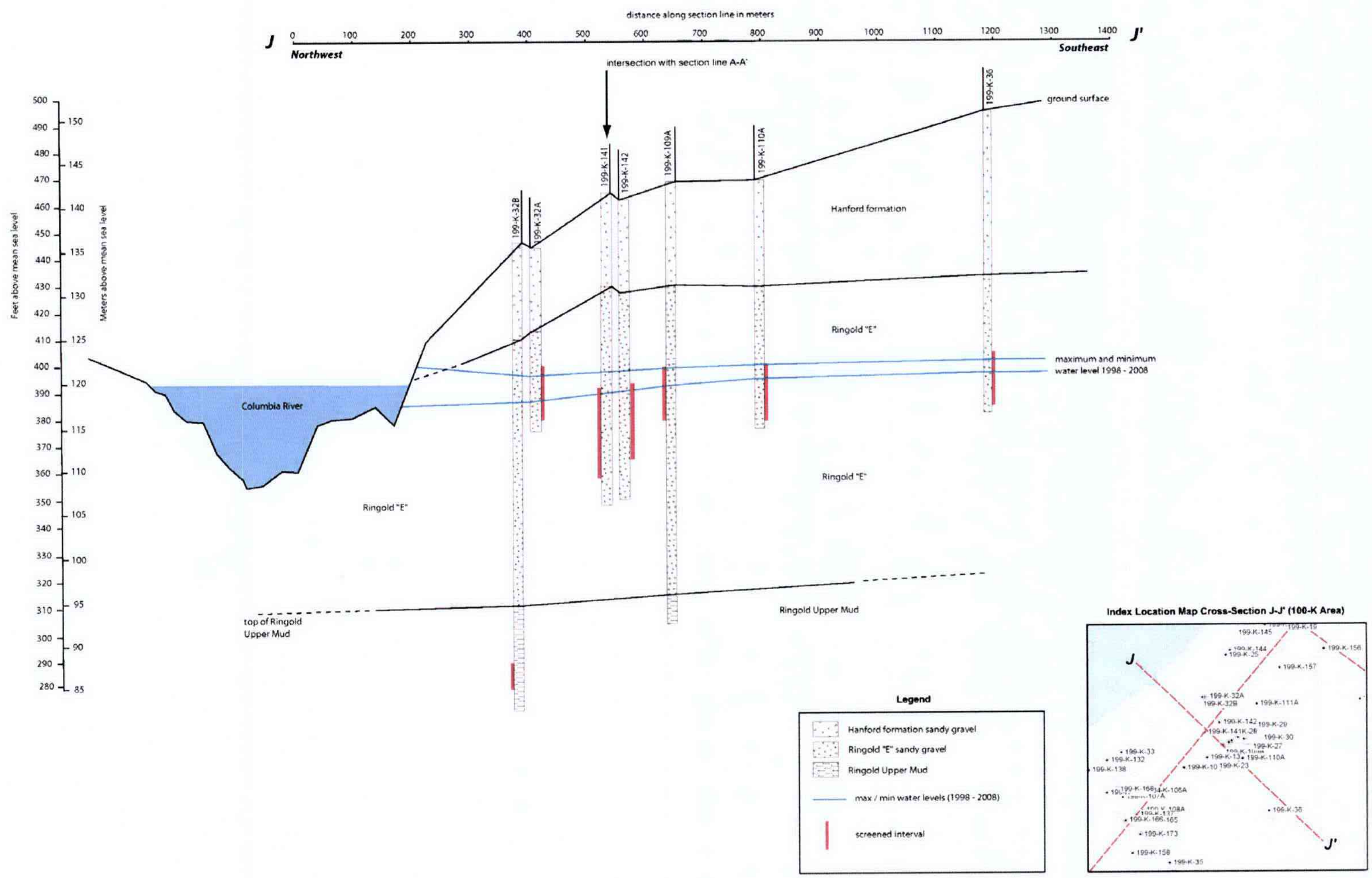


Figure 3-9. Cross-Section JJ' Depicting Hydrogeologic Unit Projections into the Columbia River, 100-KR-4 Operable Unit (after SGW-41213, Rev. 0)

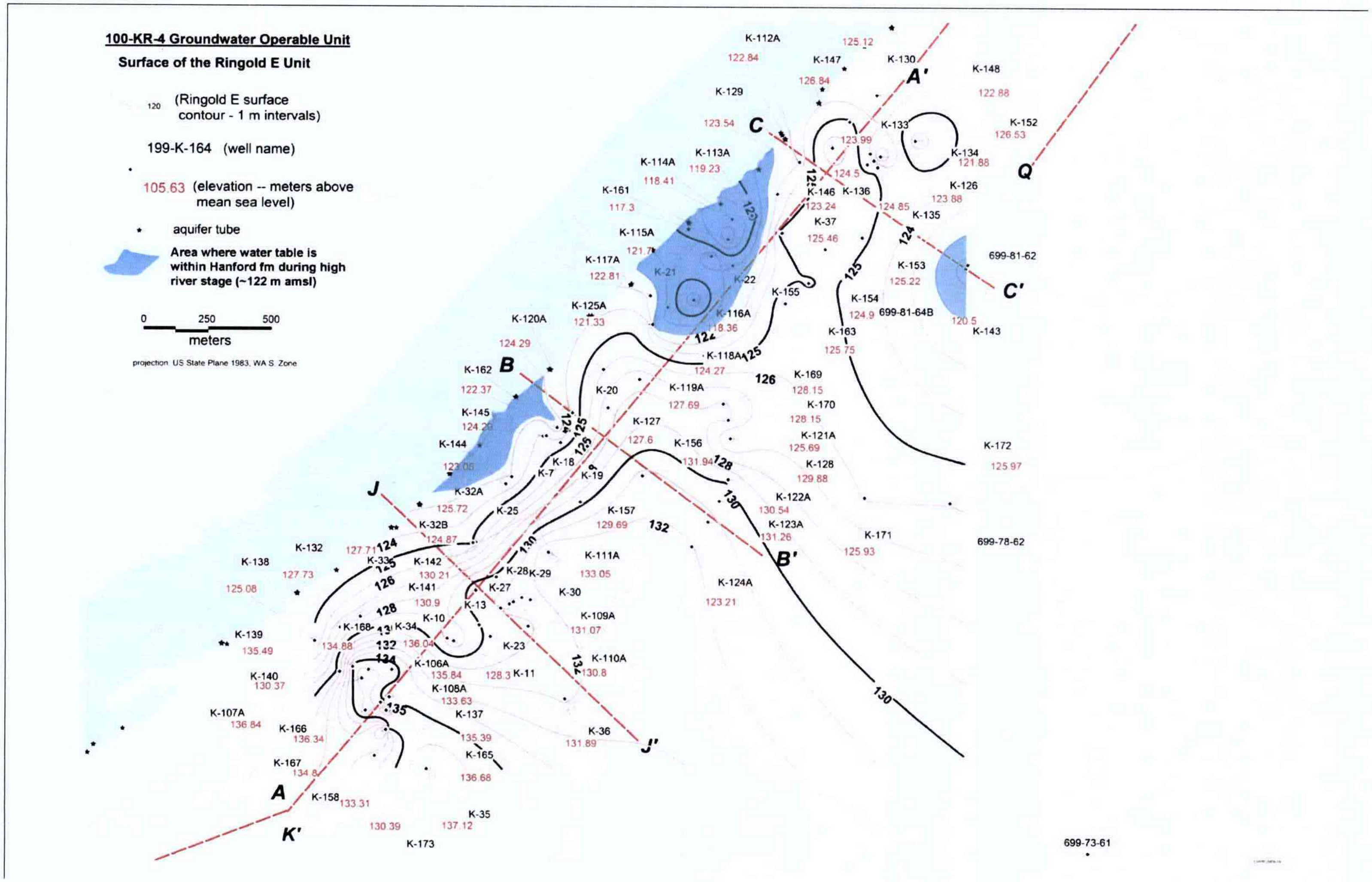


Figure 3-10. Structural Contour Map of the Hanford/Ringold Contact Surface (Disconformity), 100-KR-4 Operable Unit (after SGW-41213, Rev. 0)

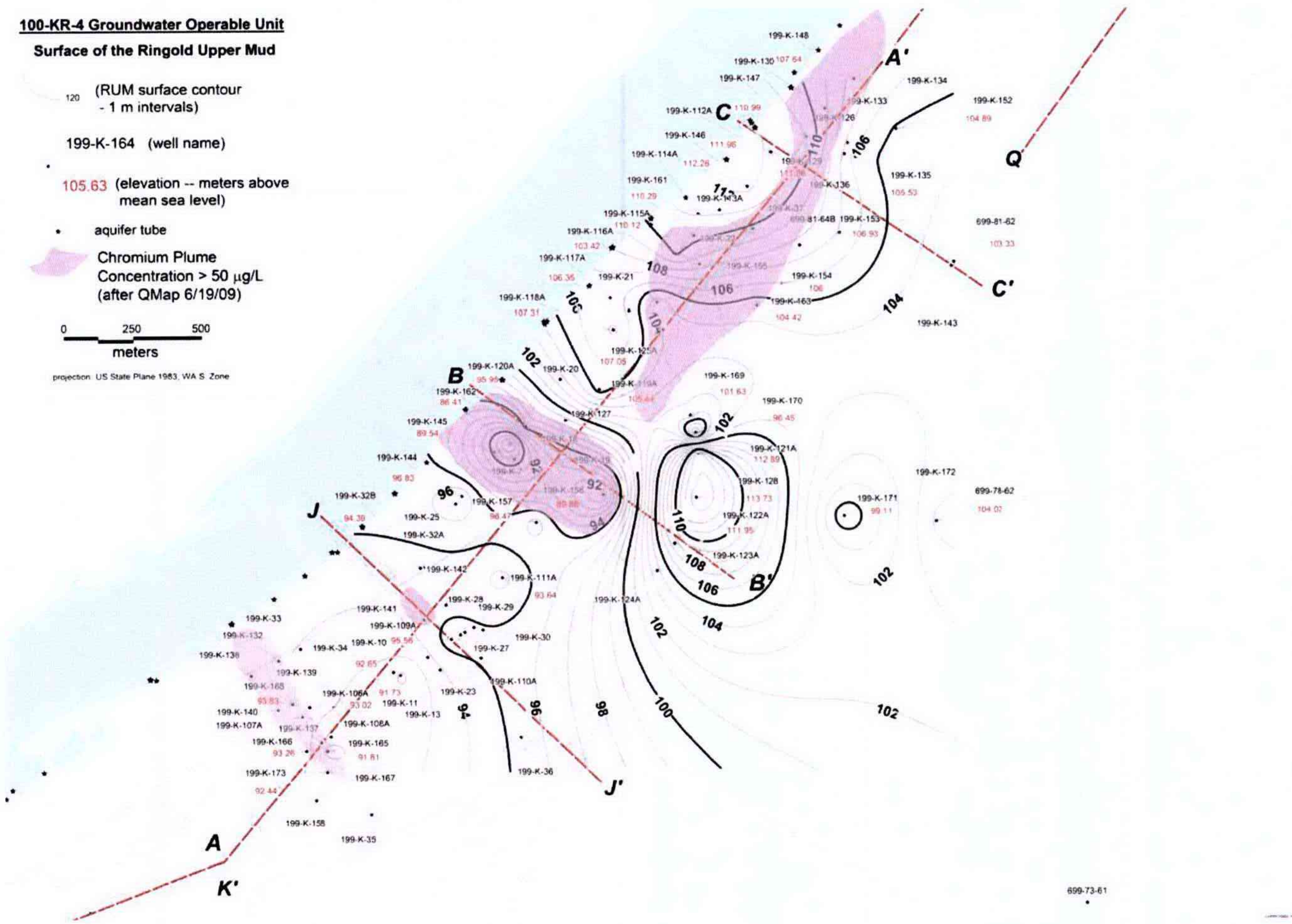


Figure 3-11. Structural Contour Map of the Ringold Upper Mud Unit Beneath the 100-KR-4 Operable Unit (after SGW-41213, Rev. 0)

Table 3-3. Geologic Data for the 100-BC-5 Groundwater OU (after SGW-44022, Rev. 1)

Well Name	Well ID	Northing (m)	Easting (m)	Well Type	Well Status	Surface Elev. (m)	Elevation Control	Stickup Data Source	Drill Depth (ft)	Drill Depth (m)	Depth to RE (ft)	Depth to RE (m)	Hf/Re Elev. (m)	Ringold E Depth Data Source	Depth to RUM (ft)	Depth to RUM (m)	RUM Elev. (m)	RUM Depth Data Source	Notes
199-B2-12	A4550	145363.68	565368.44	GW well	In use	133.93	Disc z	--	178.8	54.5	12.5	3.8	130.1	Borehole log (GRAM)	149.5	45.6	88.4	Borehole log (GRAM)	RUM depth reinterpreted; RE uncertain.
199-B2-13	A4551	145364.60	565926.88	GW well	In use	127.69	Disc z	--	40	12.2	X	X	X	N/A	NDE	NDE	<115.5	N/A	
199-B2-14	C7665	145232.26	565095.99	GW well	In use	134.30	Disc z	--	152.3	46.4	44.5	13.6	120.7	Borehole log (GRAM)	143.7	43.8	90.5	Borehole log (GRAM)	
199-B2-15	C7783	145230.48	565092.32	GW well	In use	134.27	Disc z	--	193.8	59.1	31.5	9.6	124.7	Borehole log (GRAM)	143.7	43.8	90.5	Borehole log (GRAM)	
199-B2-16	C7784	145190.68	564915.00	GW well	In use	133.37	Disc z	--	155.2	47.3	40	12.2	121.2	Borehole log (GRAM)	147	44.8	88.6	Borehole log (GRAM)	
199-B3-1	A4552	145342.08	565561.46	GW well	In use	133.97	TOC: 3 ft SU	Assumed	63	19.2	X	X	X	N/A	NDE	NDE	<114.8	N/A	Cursory log shows undifferentiated sediments; revised depth takes assumed stickup into account. RE pick in SGW-44022 does not appear to be supported by log.
199-B3-2	A9505	145326.11	565847.58	Piezometer host	Decommissioned	135.43	TOC: 1.55 ft SU	WCS	790	240.8	X	X	X	N/A	153	46.6	88.8	SGW-44022	Note that Ringold lower mud (388 ft) and basalt (656 ft) bgs are present. Appears to be nothing in the cursory log to support the RE pick in SGW-44022, elevation takes stickup into account.
199-B3-46	A4553	145369.04	565899.57	GW well	In use	134.73	Disc z	--	66.77	20.4	50	15.2	119.5	Borehole log (GRAM)	NDE	NDE	<114.4	N/A	Hf/RE contact not well defined in borehole log, fewer basalt cobbles at 50 ft bgs.
199-B3-47	A4554	145368.95	565388.66	GW well	In use	133.85	Disc z	--	61	18.6	X	X	X	N/A	NDE	NDE	<115.3	N/A	
199-B3-50	C7506	145058.21	566028.90	GW well	In use	143.02	Disc z	--	183.3	55.9	91	27.7	115.3	Borehole log (GRAM)	177	53.9	89.1	Borehole log (GRAM)	
199-B3-51	C7785	145363.88	565378.66	GW well	In use	134.04	GPS	--	156.2	47.6	13	4.0	130.1	Borehole log (GRAM)	149.5	45.6	88.5	Borehole log (GRAM)	
199-B3-52	C7843	145115.03	565391.00	--	In use	134.66	Disc z	--	60	18.3	NDE	NDE	NDE	Borehole log (GRAM)	NDE	NDE	<116.4	Borehole log (GRAM)	100-B/C Area vadose borehole completed as temporary well.
199-B4-1	A4555	144791.53	565289.81	GW well	In use	141.20	TOC: 1.3 ft SU	WCS	90	27.4	X	X	X	N/A	NDE	NDE	<113.8	N/A	Well did not reach RUM, cursory log shows undifferentiated sediments, elevation takes stickup into account.
199-B4-2	A5539	144770.89	565283.84	GW well	Decommissioned	141.35	TOC: 1 ft SU	WCS	90	27.4	X	X	X	N/A	NDE	NDE	<113.9	N/A	Cursory log shows undifferentiated sediments, elevation takes stickup into account.
199-B4-3	A4556	144771.13	565295.59	GW well	Decommissioned	141.31	TOC: 1.46 ft SU	WCS	91	27.7	X	X	X	N/A	NDE	NDE	<113.6	N/A	Cursory log shows undifferentiated sediments, elevation takes stickup into account.
199-B4-4	A4557	144479.71	565377.08	GW well	In use	144.63	TOC: 2.4 ft SU	WCS	105	32.0	X	X	X	N/A	NDE	NDE	<112.6	N/A	Hf/RE not identified in cursory log, undifferentiated sediments, elevation takes stickup into account.
199-B4-5	A5540	144349.16	565390.51	GW well	In use	147.06	Disc z	--	97.17	29.6	X	X	X	N/A	NDE	NDE	<117.4	N/A	Cursory log shows undifferentiated sediments.
199-B4-6	A4558	144382.97	565388.88	GW well	In use	147.02	Disc z	--	97.41	29.7	X	X	X	N/A	NDE	NDE	<117.3	N/A	Cursory log shows undifferentiated sediments.
199-B4-7	A5541	144382.85	565396.86	GW well	In use	147.07	Disc z	--	96.52	29.4	X	X	X	N/A	NDE	NDE	<117.7	N/A	Cursory log shows undifferentiated sediments.
199-B4-8	A4559	144653.79	565578.45	GW well	In use	144.46	Disc z	--	90.4	27.6	88	26.8	117.6	Borehole log (GRAM)	NDE	NDE	<116.9	N/A	RE interpreted to be 8 ft deeper than shown in SGW-44022, pronounced lithologic change at 88 ft bgs.
199-B4-9	A4560	144563.93	565395.64	GW well	Decommissioned	143.81	Disc z	--	92.8	28.3	X	X	X	N/A	NDE	NDE	<115.5	N/A	RE contact not identified in borehole log.
199-B4-10	A5542	144516.37	565396.56	GW well	In use	144.69	Disc z	--	23.5	7.2	X	X	X	N/A	NDE	NDE	<137.5	N/A	

Table 3-3. Geologic Data for the 100-BC-5 Groundwater OU (after SGW-44022, Rev. 1)

Well Name	Well ID	Northing (m)	Easting (m)	Well Type	Well Status	Surface Elev. (m)	Elevation Control	Stickup Data Source	Drill Depth (ft)	Drill Depth (m)	Depth to RE (ft)	Depth to RE (m)	Hf/Re Elev. (m)	Ringold E Depth Data Source	Depth to RUM (ft)	Depth to RUM (m)	RUM Elev. (m)	RUM Depth Data Source	Notes
199-B4-14	**C7786**	**144313.98**	**564969.25**	GW well	In use	**144.97**	**Disc z**	--	**95.8**	**29.2**	**NDE**	**NDE**	**NDE**	**N/A**	**NDE**	**NDE**	**<115.8**	**N/A**	
199-B4-15	C7846	144551.98	565439.68	--	In use	144.26	Disc z	--	84.3	25.7	NDE	NDE	NDE	N/A	NDE	NDE	<118.6	N/A	100-B/C Area vadose borehole completed as temporary well.
199-B5-1	A4561	144764.90	564878.15	GW well	In use	139.04	TOC; 2.8 ft SU	WCS	151	46.0	X	X	X	N/A	NDE	NDE	<93.0	N/A	Hf/RE not identified in cursory log in well construction and completion summary. elevation takes stickup into account.
199-B5-2	A4562	144939.70	565405.43	GW well	In use	139.80	Disc z	--	75	22.9	NDE	NDE	NDE	N/A	NDE	NDE	<116.9	N/A	
199-B5-5	C7505	144955.22	564723.24	GW well	In use	135.42	Disc z	--	214.8	65.5	53	16.2	119.3	Borehole log (GRAM)	205	62.5	72.9	Borehole log (GRAM)	
199-B5-6	**C7507**	**144316.44**	**564967.70**	GW well	In use	**144.97**	**Disc z**	--	**195.5**	**59.6**	**93**	**28.3**	**116.6**	**Borehole log (GRAM)**	**191**	**58.2**	**86.8**	**Borehole log (GRAM)**	
199-B5-8	**C8244**	**143585.00**	**566013.65**	GW well	In use	**153.93**	**GPS**	--	**230.6**	**70.3**	**200**	**61.0**	**93.0**	**Borehole log**	**222.5**	**67.8**	**86.1**	**Borehole log**	
199-B8-6	A4563	144157.79	564498.83	GW well	In use	145.02	Disc z	--	91	27.7	75	22.9	122.2	Gross gamma log (GRAM)	NDE	NDE	<117.3	N/A	Borehole log has basalt dominated sediments to TD. SGW-44022 shows RE slightly deeper at 78 ft bgs.
199-B8-9	**C7508**	**144054.72**	**565276.56**	GW well	In use	**150.99**	**Disc z**	--	**219.5**	**66.9**	**115**	**35.1**	**115.9**	**Borehole log (GRAM)**	**211.5**	**64.5**	**86.5**	**Borehole log (GRAM)**	**Hf/RE not identified in log.**
199-B9-1	A4564	144029.69	565501.96	GW well	Decom mission ed	151.37	TOC; 2.9 ft SU	WCS	117	35.7	X	X	X	N/A	NDE	NDE	<115.7	N/A	SGW-44022 shows RE at 88 ft; does not appear to be supported by driller's log; elevation takes stickup into account.
199-B9-2	A4565	144078.08	565534.79	GW well	In use	151.73	Disc z	--	118	36.0	88	26.8	124.9	SGW-44022	NDE	NDE	<115.8	N/A	RE interpretation in SGW-44022 (from DOE/RL-93-37) unlikely as sediments from 88 ft bgs to TD described in borehole log as 80% to 90% basalt cobbles (more likely Hanford formation). SGW-44022 interpretation not based on slug test as proposed depth is above water table, no discontinuities in gross gamma log at proposed depth.
C7842	**C7842**	**145327.43**	**565391.93**	--	Decom mission ed	**133.42**	**GPS**	--	**55**	**16.8**	**NDE**	**NDE**	**<116.0**	**N/A**	**NDE**	**NDE**	**<116.0**	**N/A**	**100-B/C Area vadose borehole**
C7844	**C7844**	**144761.31**	**565290.19**	--	Decom mission ed	**141.36**	**GPS**	--	**73.1**	**21.8**	**NDE**	**NDE**	**<119.1**	**N/A**	**NDE**	**NDE**	**<119.1**	**N/A**	**100-B/C Area vadose borehole**
C7845	**C7845**	**144638.85**	**565355.92**	--	Decom mission ed	**143.10**	**GPS**	--	**78.9**	**23.3**	**NDE**	**NDE**	**<119.1**	**N/A**	**NDE**	**NDE**	**<119.1**	**N/A**	**100-B/C Area vadose borehole**
C7849	**C7849**	**144026.97**	**565397.34**	--	Decom mission ed	**151.81**	**Disc z**	--	**107.7**	**31.4**	**NDE**	**NDE**	**<119.0**	**Borehole log (GRAM)**	**NDE**	**NDE**	**<120.4**	**N/A**	**100-B/C Area vadose borehole; transitional gravels at Hf/RE contact.**
C8239	**C8239**	**565331.7**	**144527.6**	--	Decom mission ed	**144.05**	**Disc z**	--	**82.3**	**25.1**	**NDE**	**NDE**	**NDE**	**N/A**	**NDE**	**NDE**	**<119.0**	**N/A**	**100-B/C Area vadose borehole.**
699-63-89	A8956	142576.97	562902.06	GW well	Decom mission ed	156.24	TOC; 3.3 ft SU	WCS	220	67.1	100	30.5	125.8	SGW-44022, geophysical logs (GRAM)	NP	NP	NP	N/A	Neutron, density, and gamma logs all show strong discontinuity at 100 ft bgs; SGW-44022 (from DOE/RL-93-37) indicates RE found at depth of 110 ft bgs, well drilled to basalt at 209 ft bgs, no evidence of RUM.
699-63-90	A5293	142612.35	562367.22	GW well	In use	156.28	TOC; 1.9 ft SU	WCS	253	77.1	105	32.0	124.3	Geophysical logs (GRAM)	NP?	NP?	NP?	Driller's log unclear	SGW-44022 indicates RE at 135 ft bgs (from DOE/RL-93-37), nothing in cursory log in as-built to support this interpretation. Modest discontinuities in gamma, neutron, and density logs at 105 ft bgs interpreted to represent the top of the RE. Basalt at 238 ft.

Table 3-3. Geologic Data for the 100-BC-5 Groundwater OU (after SGW-44022, Rev. 1)

Well Name	Well ID	Northing (m)	Easting (m)	Well Type	Well Status	Surface Elev. (m)	Elevation Control	Stickup Data Source	Drill Depth (ft)	Drill Depth (m)	Depth to RE (ft)	Depth to RE (m)	Hf/Re Elev. (m)	Ringold E Depth Data Source	Depth to RUM (ft)	Depth to RUM (m)	RUM Elev. (m)	RUM Depth Data Source	Notes
699-63-92	A5294	142637.44	561559.74	GW well	In use	151.84	TOC, 2.6 ft SU	WCS	186	56.7	X	X	X	N/A	NP	NP	NP	N/A	Basalt at 150 ft bgs. RUM not present. Hf/RE contact not identified.
699-65-83	A5303	143249.09	564590.47	GW well	In use	148.10	TOC, 3.1 ft SU	WCS	121	36.9	85	25.9	122.2	Geophysical logs (GRAM)	NDE	NDE	<111.2	N/A	SGW-444022 indicates RE at 97 ft bgs (from DOE/RL-93-37), nothing in log in as-built to support this interpretation; discontinuities in density log at 85 ft bgs, neutron log at 82 ft bgs, and gamma log at 87 ft bgs are interpreted to represent top of RE.
699-66-91	A5311	143476.80	562174.81	GW well	In use	142.62	TOC, 3.1 ft SU	WCS	190	57.9	78	23.8	118.8	Geophysical logs (GRAM)	NP	NP	NP	N/A	SGW-44022 indicates possible RE at 57 ft bgs, cursory log in as-built does not support this interpretation. Neutron and density logs show discontinuities at 78 ft bgs (matching a lithology change) interpreted as top of RE. Basalt at 98 ft.
699-67-86	A5313	143873.05	563661.65	GW well	In use	144.47	TOC, 1.8 ft SU	WCS	467	142.3	X	X	X	Geophysical logs (GRAM)	247	75.3	69.2	Well summary sheet (GRAM)	SGW-44022 indicates RE at 79 ft bgs (from DOE/RL-93-37), cursory log in as-built does not support this interpretation. RUM assumed to be first silt layer at 247 ft bgs.
699-71-77	A5322	145098.61	566401.95	GW well	In use	144.23	TOC, 2.4 ft SU	WCS	300	91.4	80.0	24.4	119.8	Geophysical logs (GRAM)	180	54.9	89.4	Well summary sheet (GRAM)	RE interpretation of 94 ft bgs in SGW-44022 (from DOE/RL-93-67) not supported by cursory log in as-built or by geophysical log;, neutron and gamma logs show a discontinuity at 80 ft bgs, which is interpreted to represent the top of the RE; RUM interpretation from borehole log is 3 ft deeper than depth shown in SGW-44022.
699-72-92	A5325	145359.75	561839.42	GW well	In use	137.20	TOC, 2.8 ft SU	WCS	200	61.0	155	47.2	90.0	SGW-44022	NDE	NDE	<72.2	N/A	Based on cemented gravels described in cursory drill log in as-built, seems quite deep and interpretation may not be correct, no other useful data (e.g., geophysical logs, etc.).

Notes:

1. **Bold** well numbers/rows indicate new wells added to this revision.
2. The references cited in this table are included in the reference list (Chapter 12); SGW-44022 cited above is Revision 0.

bgs = below ground surface
Hf/RE = Hanford formation/Ringold Formation unit E
GPS = global positioning system
GW = groundwater
ID = identification
N/A = not applicable
NDE = not deep enough
NP = not present
RE = Ringold Formation unit E
RUM = Ringold Formation upper mud unit
SU = casing stickup
TOC = top of well casing
WCS = well construction summary report
X = not available

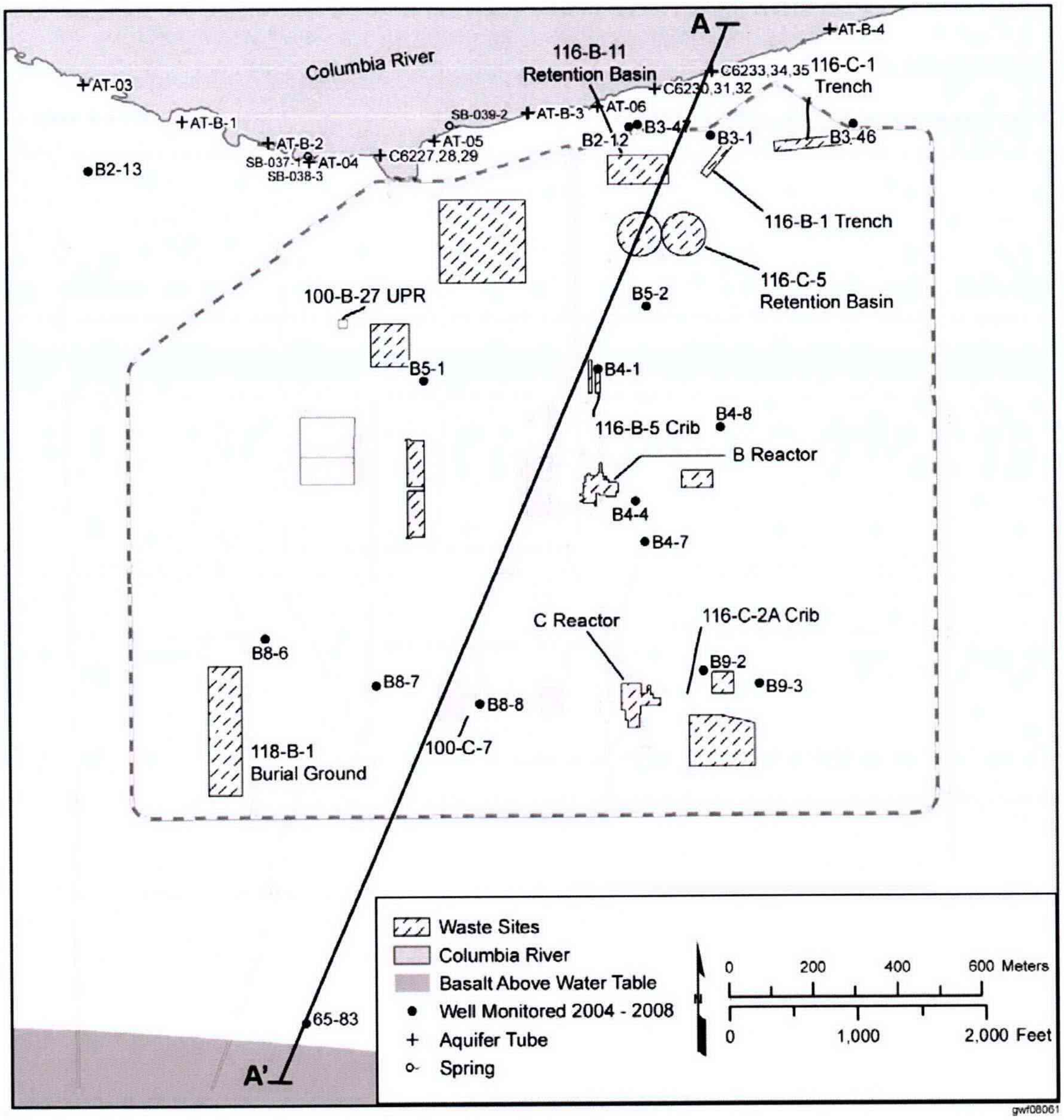


Figure 3-12. 100-BC-5 Operable Unit Geologic Cross-Section Location

Ringold Formation

In the 100-BC-5 OU and vicinity, the Ringold Formation consists of semi-indurated clay, silt, fine- to coarse-grained sand, and pebble to cobble-size gravel. These sediments are subdivided into five facies associations that are defined on the basis of lithology, petrology, stratification, and pedogenic alteration (DOE/RL-2008-46).

The Ringold Formation is estimated to be approximately 182 m (600 ft) thick beneath the 100-BC-5 OU based on data from only one deep borehole, well 199-B3-2. The Hanford/Ringold contact surface ranges in depth from approximately 4 m (13 ft) near the Columbia River to 61 m (200 ft) in well 199-B5-8, southeast of the 100-B/C Area. Information about the thickness of the various Ringold Formation units in the 100-BC-5 OU is limited. Table 3-3 presents available geologic information from wells drilled within the 100-BC-5 OU. The oldest Ringold Formation units are composed of thick sequences of paleosol and overbank sediment (silt and clay), interspersed with laterally discontinuous, coarse-grained sediments (DOE/RL-93-37, *Limited Field Investigation Report for the 100-BC-5 Operable Unit*). Distinguishing sandy beds within the RUM from Ringold units C and B is not always possible. Similarly, silts and clays of the RUM may grade into deeper silt and clay units, making correlation of the units between boreholes difficult. In the 100-B/C Area, only well 199-B3-2 penetrated the entire Ringold Formation. In this well, the RUM is interpreted to be approximately 34 m (110 ft) thick. The upper 0.5 m to 4 m (2 ft to 13 ft) of the RUM in the 100-B/C Area is comprised of clay and silt, and the deeper sediments range from silty sandy gravel to silty sand. The Ringold unit E, composed of unconsolidated to slightly indurated silty-sandy gravel, overlies the RUM surface (Figures 3-1 and 3-13).

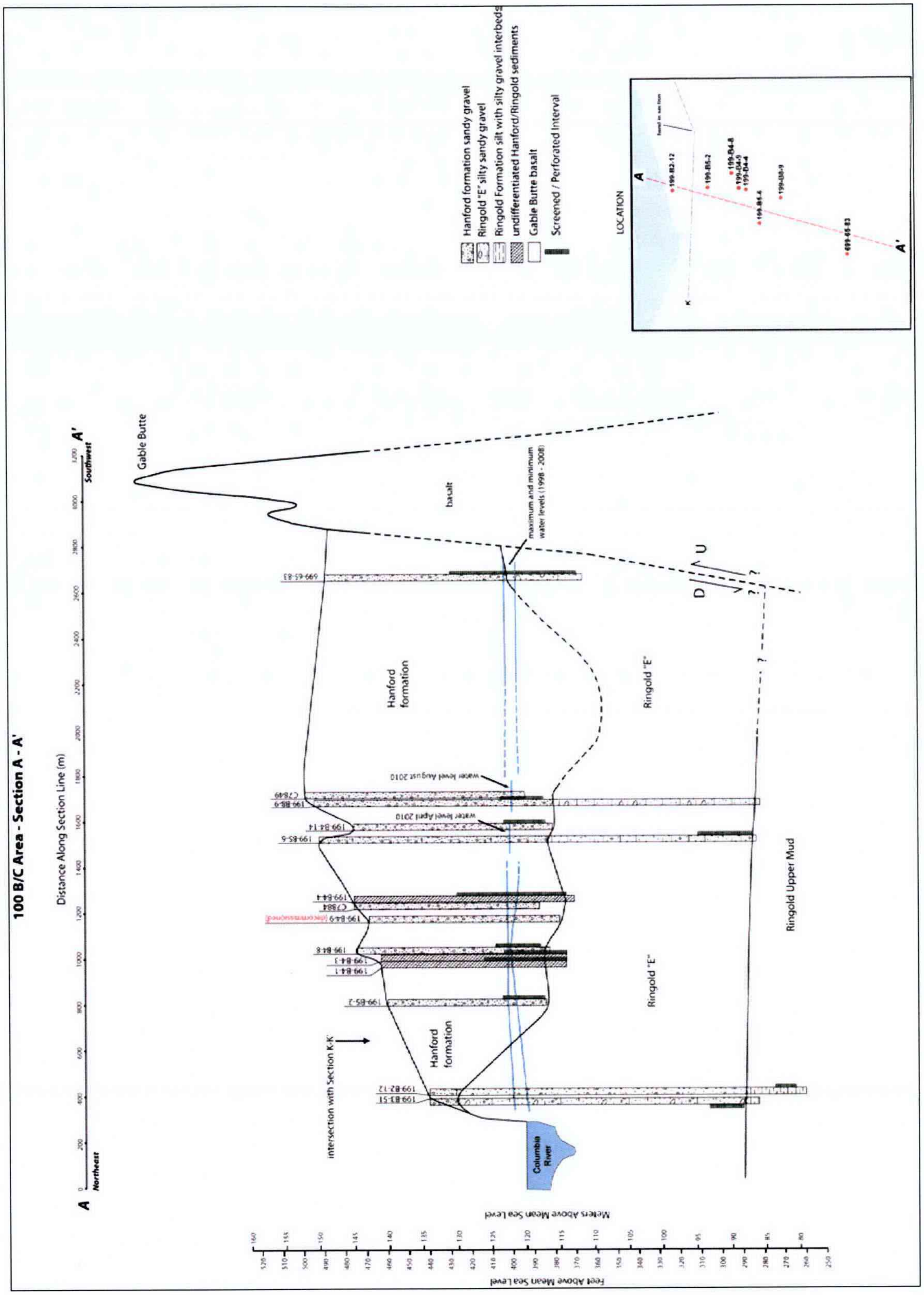


Figure 3-13. 100-BC-5 Operable Unit Hydrogeologic Cross-Section (after SGW-44022, Rev. 1)

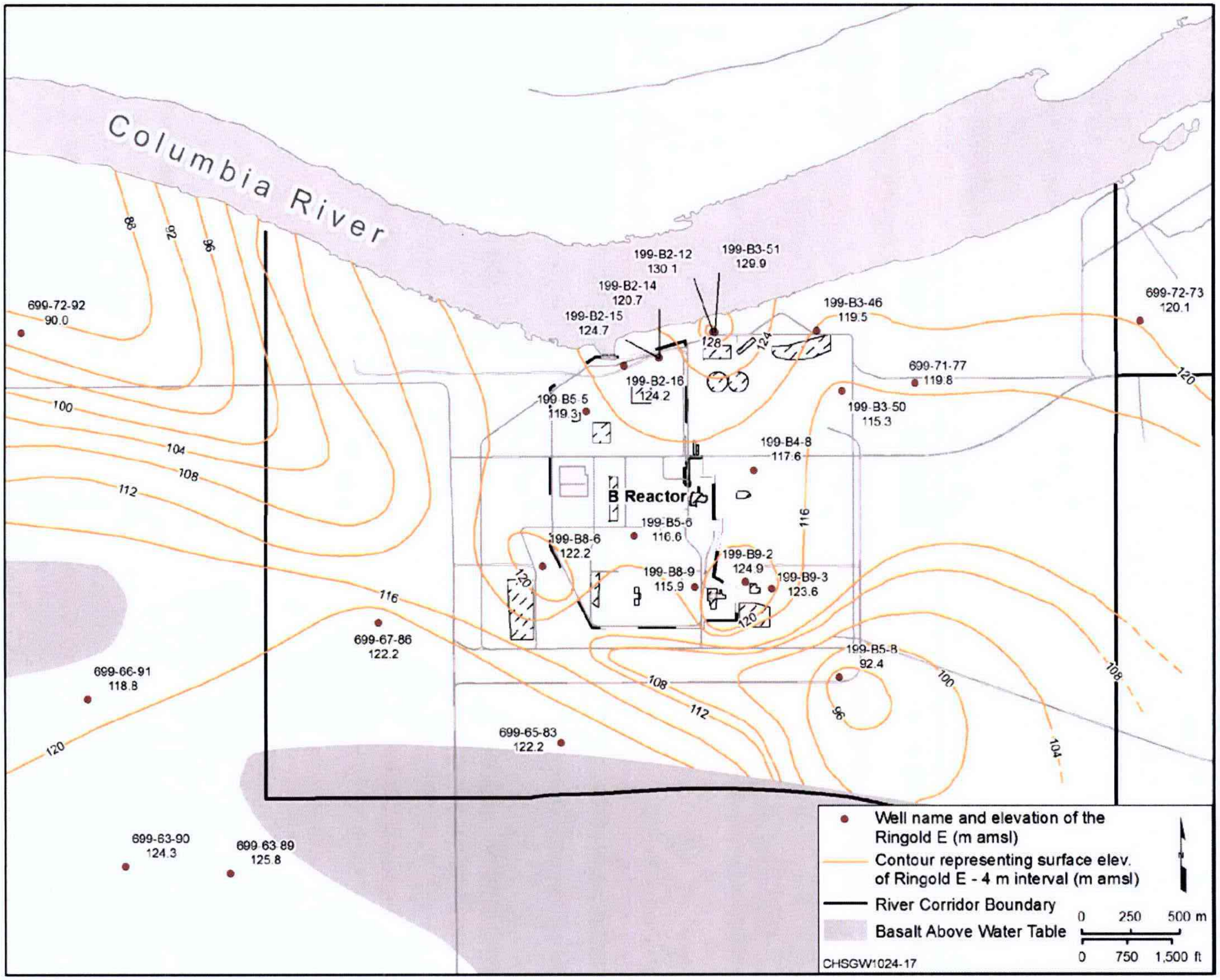


Figure 3-14. Hydrogeologic Surface (Structure) Map of the Hanford/Ringold Contact, 100-BC-5 Operable Unit (after SGW-44022, Rev. 1)

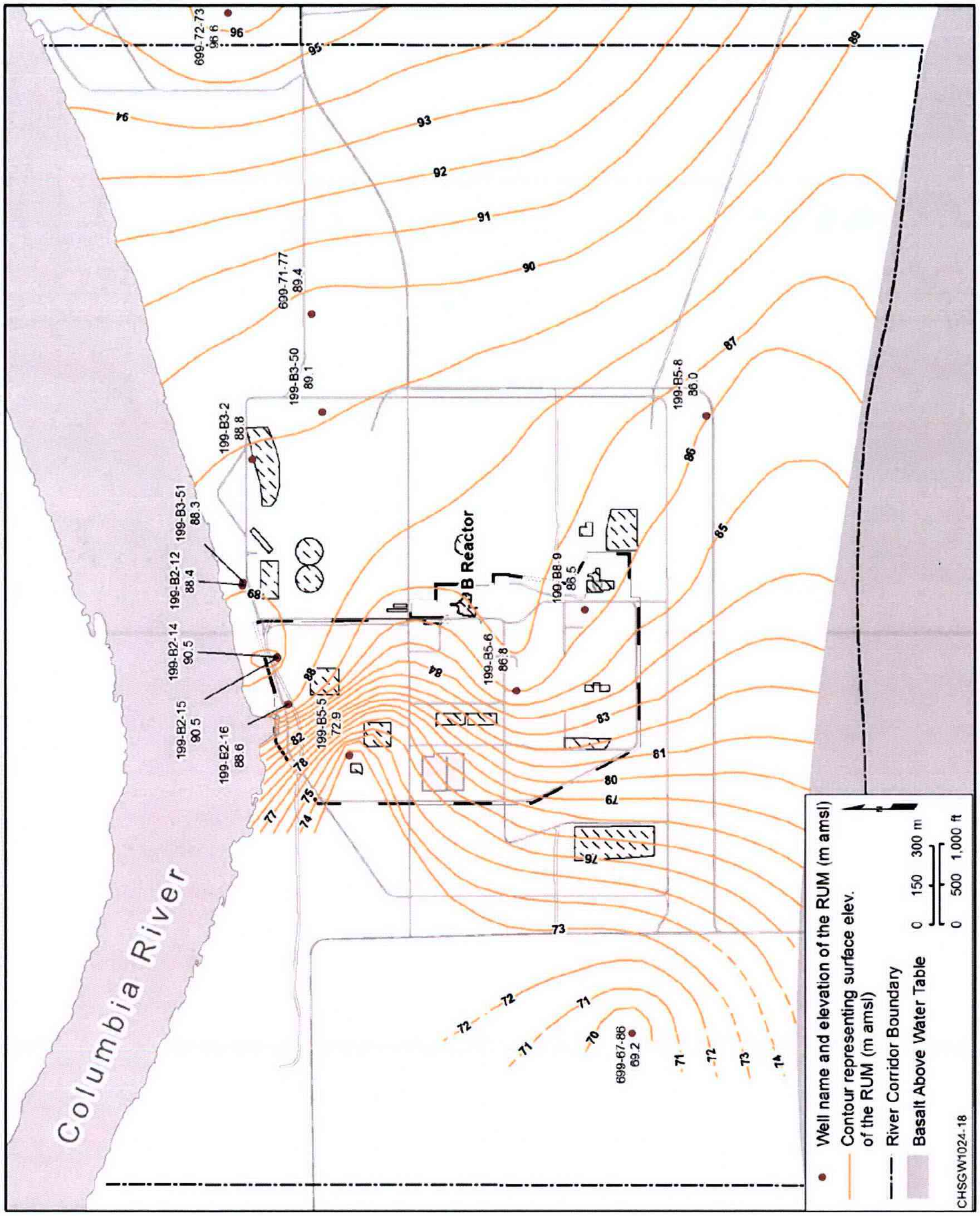


Figure 3-15. Hydrogeologic Surface (Structure) Map of the Ringold Upper Mud Unit, 100-BC-5 Operable Unit (after SGW-44022, Rev. 1)

Hanford/Ringold Contact

At the 100-BC-5 OU Hanford formation gravels unconformably overly the Ringold unit E (i.e., Hanford/Ringold contact). The contact between Ringold unit E and the Hanford formation (i.e., the Hanford/Ringold contact or Ringold unit E structure map [Figure 3-14]) is often interpreted as buried paleoflood or river channels that, if occurring below the water table, could become preferential pathways for contaminated groundwater to migrate to the Columbia River (PNNL-14702). The Hanford/Ringold contact surface is important because the saturated hydraulic conductivity of the Hanford formation gravel-dominated sequence is typically significantly higher than the more compacted and locally cemented Ringold unit E and the deeper Ringold Formation undifferentiated fine-grained units (i.e., RUM). However, within the 100-BC-5 OU the Hanford formation is often difficult to differentiate from the Ringold Formation (i.e., unit E) because both are gravel-dominated sediment sequences; as a result, many of the borehole logs do not distinguish between the two formations. The units are differentiated based on characteristics such as a basalt clast content, gravel content, coloration, and cementation. The Hanford formation is typically less cemented than the Ringold Formation and has greater gravel content, but cable-tool drilling can disrupt the integrity of these characteristics. Unconsolidated boulder gravel in the upper 6 to 15 m (20 to 50 ft) of the Hanford Formation demonstrates the high-energy depositional environment created during the Missoula paleo-floods: these deposits can be difficult to penetrate by drilling methods (WHC-SD-EN-TI-155, *Geology of the 100-K Area, Hanford Site, South-Central Washington*).

Hydrogeologic Surface (Structure) Maps

At the 100-BC-5 OU, the unconfined aquifer is contained within Ringold unit E and the saturated Hanford formation (Figure 3-14). The elevation of this contact is close to the water table in some areas and may be above or below the water table. The Ringold unit E structure map indicates a northwest-southeast trending low that generally parallels the Gable Butte/Gable Mountain basalt uplift. Currently, there is little well control within this low, but existing and new well data suggest that this lower elevation region may reflect remnants of a paleo-flood or ancestral river channel (Figure 3-14). Preferential flow may occur in low areas such as this where the Hanford/Ringold contact is below the water table. The top of the low-permeability RUM defines the base of the unconfined aquifer (Figure 3-15). The unconfined aquifer ranges in thickness from about 29 m (95 ft) to more than 51 m (167 ft). The RUM surface generally dips to the west beneath the 100-BC-5 OU.

Water-bearing units within and beneath the RUM form confined to semiconfined conditions within the lower suprabasalt aquifer. The hydraulic conductivity of these older Ringold units is generally considerably lower than that of the overlying unconfined aquifer. The base of the Ringold Formation (and hence the base of the suprabasalt aquifer system) is defined at the top of basalt, which is estimated to be approximately 200 m (660 ft) below ground surface (bgs) in well 199-3-2. At the southern boundary of the OU, the Saddle Mountains Basalt is exposed at Gable Butte and forms the southern no-flow boundary of the OU and also the southern limit of the entire suprabasalt aquifer system (Figure 3-13). Gable Butte was formed by regional tectonic activity that created a warped and faulted basalt surface and formed the southern limit and boundary of the Wahluke syncline to the north.

3.2.4 100-NR-2 Operable Unit Hydrogeology

The location of cross-sections developed to illustrate the hydrogeology for the 100-NR-2 OU are shown in Figure 3-16. The hydrogeologic cross-sections (Figures 3-17 through 3-20) are oriented perpendicular (D-D') and parallel (A-A', B-B', and C-C') to the Columbia River and illustrate the variable thickness of the uppermost unconfined aquifer located within the Ringold Unit E above the thick, low-permeability RUM sequence.

The geologic units that comprise the uppermost (suprabasalt) aquifer system (Figure 3-1) within the 100-NR-2 OU are described below. The properties of these geologic units influence the distribution of contamination in the subsurface. The description begins with the youngest units at the surface located within the overlying vadose zone and then progresses to the oldest units making up the lower-confining unit at the base of the suprabasalt aquifer system. The composite thickness of the sediments overlying the basalt in the 100-N Area ranges between 152 and 175 m (500 and 574 ft).

Backfill and Holocene (Recent) Deposits

Recent backfill sand and gravel and/or Holocene deposits consisting of Columbia River deposits and eolian loess (windblown), silt, sand, and gravel form surficial deposits across the 100-NR-2 OU (Figure 3-1). Because of anthropogenic activities associated with construction of the reactors (dating to the 1940s) and supporting facilities, the Holocene deposits within the area have been removed or altered. Construction backfill near manmade structures varies in depth, depending on the excavated depth of waste sites and building foundations. Additionally, backfill material may cover spatially larger graded areas to a depth of up to 0.3 m (1 ft). Outside of those areas, the Holocene deposits are relatively thin, ranging up to approximately 2 m (6.5 ft) in thickness.

Hanford Formation

The Hanford formation overlies the Ringold Formation beneath the 100-NR-2 OU and consists of boulders, gravel, sand, and silt deposited by cataclysmic Ice Age floodwaters (Figure 3-1) during the Pleistocene epoch (Volume 1 of DOE/RW-0164, *Site Characterization Plan: Reference Repository Location, Hanford Site, Washington*). As for the other OUs, the Hanford formation is divided into three main lithologic facies: gravel-dominated, sand-dominated, and interbedded sand- to silt-dominated. While all three facies are present in the area, the gravel- and sand-dominated sequences are the most prolific beneath the 100-NR-2 OU. The Hanford formation comprises most of the vadose zone throughout the area. The thickness of the Hanford formation ranges from approximately 6 to 23 m (20 to 75 ft) in the 100-N Area (DOE/RL-2008-46-ADD5).

Ringold Formation

The Ringold Formation directly overlies the Columbia River Basalt Group. In the 100-NR-2 OU and vicinity, the Ringold Formation consists of fluvial-lacustrine-derived (stream-lake) sediments that range from non-indurated to semi-indurated (loose to semi-hardened) clay, silt, fine- to coarse-grained sand, and pebble- to cobble-size gravel. These sediments are subdivided into five facies associations that are defined on the basis of lithology, petrology, stratification, and pedogenic alteration (DOE/RL-2008-46). Two Ringold Formation units (Unit E and the RUM) have been defined within the 100-NR-2 OU.

The Ringold Formation is estimated at a thickness of approximately 148 to158 m (486 to 518 ft) beneath the 100-NR-2 OU (DOE/RL-2008-46-ADD5). The Hanford/Ringold contact surface ranges in depth from less than 1 m (3 ft) bgs at the Columbia River to over 17 m (56 ft) bgs. The oldest Ringold Formation units are composed of thick sequences of paleosol (soils) and overbank sediment (silt and clay), interspersed with laterally discontinuous coarse-grained sediments (DOE/RL-93-37, *Limited Field Investigation Report for the 100-BC-5 Operable Unit*). The uppermost fine-grained unit, the RUM, forms the base of the unconfined aquifer system within the OU. The RUM (including the lower, fine-grained Ringold Formation sediment) is up to 139 m (456 ft) in thickness in the 100-NR-2 OU (DOE/RL-2008-46-ADD5).

The Ringold Unit E is composed of unconsolidated to slightly indurated, fluvially deposited, silty-sandy gravel and typically overlies the RUM surface and forms the uppermost unconfined aquifer system within the 100-NR-2 OU (Figures 3-17 and 3-20). Table 3-1 presents available geologic contact information from wells drilled within the 100-NR-2 OU. Hanford formation gravel unconformably overlies the Unit E (i.e., Hanford/Ringold contact) within the OU.

Hanford/Ringold Contact

The contact between Hanford formation and the Ringold Formation (Hanford/Ringold contact) is important because the hydraulic properties of the Hanford formation gravel-dominated sequence generally create more transmissive and permeable conditions than the more compacted and locally cemented Ringold Unit E and the underlying low-permeability, deeper, fine-grained units (e.g., the RUM). Where the Hanford/Ringold contact is present, it can affect contaminant transport in the vadose zone and groundwater. The Hanford/Ringold contact surface often occurs as buried paleo flood and/or ancestral Columbia River channels that, if occurring below the water table, can become preferential pathways for contaminated groundwater to migrate to the Columbia River (PNNL-14702). However, in the 100-NR-2 OU the water table is located below the Hanford/Ringold contact.

Within the 100-NR-2 OU, the Hanford formation directly overlies the Ringold Unit E. In the 100-NR-2 OU, the Hanford/Ringold contact is within the lower vadose zone above the water table. The units are differentiated based on characteristics such as a basalt clast content, gravel content, coloration, and cementation. The Hanford formation is typically less cemented than the Ringold Formation and has greater basalt/gravel content, but cable-tool drilling can disrupt the integrity of these characteristics. Unconsolidated boulder gravel in the upper 6 to 15 m (20 to 50 ft) demonstrates the high-energy depositional environment created during the Missoula paleo-floods (Hanford formation). Older borehole data do not always document these characteristics (e.g., old drillers' logbooks), so the Hanford/Ringold contact may not be determined in some borehole logs and on cross-sections and maps.

Hydrogeologic Surface (Structure) Maps

At the 100-NR-2 OU, the unconfined aquifer - contained primarily within the saturated Ringold Unit E - is the most significant hydrostratigraphic unit relating to groundwater contaminant migration and forms the unconfined portion of the suprabasalt aquifer system (Figures 3-17 through 3-21). To date, no distinct preferential groundwater flow paths have been defined in the 100-NR-2 OU. Existing contaminant plumes migrate more or less downgradient from the source directly toward the Columbia River.

The surface of the low-permeability RUM defines the base of the unconfined aquifer in the 100-NR-2 OU (Figure 3-22). The RUM surface elevation ranges from approximately 106 to 109 m (348 to 358 ft) within the 100-NR-2 OU, such that the unconfined aquifer (the interval above the RUM) ranges in thickness from less than 1 m (3 ft) to greater than 11.5 m (38 ft). The bases of the Ringold Formation and the suprabasalt aquifer system are defined at the top of basalt, which is approximately 152 to 175 m (499 to 574 ft) bgs.

Within the unconfined aquifer, groundwater flows from regions of higher head south-southeast of the 100-N Area, toward the Columbia River, exhibiting an average hydraulic gradient of about 0.0012. Near the river, the unconfined aquifer is influenced by seasonal and diurnal changes in river stage that create riverbank storage and localized groundwater flow reversals. Within the 100-N Area, groundwater flow is more-or-less perpendicular to (and from) the Columbia River. The Ringold Formation units beneath the RUM form confined to semi-confined conditions (aquitard) within the lower suprabasalt aquifer. The transmissivities of these older Ringold units are assumed to be lower than that of the upper unconfined aquifer based on comparative data from other areas.

3.2.5 100-FR-3 Operable Unit Hydrogeology

This section briefly describes the geologic units that comprise the suprabasalt aquifer system (Figure 3-1) and contain contaminants migrating within the 100-FR-3 OU. The properties of these geologic units influence the distribution of contamination in the subsurface. The following description begins with the youngest units at the surface located within the vadose zone, and progresses to the oldest units that comprise the lower-confining unit at the base of the suprabasalt aquifer system. One well - well 699-80-43P (located 2.8 km [1.7 mi] west of the 100-F Area) - penetrated the entire suprabasalt sediment sequence (i.e., Hanford formation and Ringold Formation). The thickness of the sediments overlying the basalt at this location is approximately 134 m (440 ft). Cross-sections developed to illustrate the hydrogeology for the 100-FR-3 OU are shown in Figure 3-23. Hydrogeologic cross-sections R-R' and S-S'(Figures 3-24 and 3-25) are oriented perpendicular and parallel to the Columbia River, respectively, and illustrate the variable thickness of the uppermost unconfined aquifer located above the thick, low-permeability Ringold upper mud unit (RUM) sequence.

Backfill and Holocene (Recent) Deposits

Recent backfill sand and gravel and/or Holocene deposits consisting of Columbia River deposits and eolian loess (windblown), silt, sand, and gravel form surficial deposits across the 100-FR-3 OU (Figure 3-1). Because of anthropogenic activities associated with construction of the reactors and supporting facilities dating to the 1940s, the Holocene deposits within the area have been removed or altered. Construction backfill is located near manmade structures and varies in depth, depending on the excavated depth of waste sites and building foundations. Additionally, backfill material may cover spatially larger graded areas to a depth of up to 0.3 m (1 ft). Outside of those areas, the Holocene deposits are relatively thin, ranging up to a maximum thickness of approximately 2 m (6.5 ft).

Hanford Formation

The Hanford formation overlies the Ringold Formation beneath the 100-FR-3 OU and consists of boulders, gravel, sand, and silt deposited by cataclysmic Ice Age flood waters (Figure 3-1) during the Pleistocene epoch (DOE/RW-0164, *Site Characterization Plan: Reference Repository Location, Hanford Site, Washington*, Vol. 1). As for the other 100 Area OUs, the Hanford formation is divided into gravel-dominated, sand-dominated, and interbedded sand- to silt-dominated lithofacies (DOE/RL-2002-39, *Standardized Stratigraphic Nomenclature for Post-Ringold- Formation Sediments Within the Central Pasco Basin*). While all three facies are present in the area, the gravel- and sand- dominated sequences are the most prolific beneath the 100-FR-3 OU. The Hanford formation comprises most of the vadose zone and the uppermost unconfined aquifer throughout the area. The thickness of the Hanford formation ranges from approximately 8 to 24 m (25 to 80 ft) in the 100-F Area (WHC-SD-EN-TI-221, *Geology of the 100-FR-3 Operable Unit, Hanford Site, South-Central Washington*).

Ringold Formation

The Ringold Formation directly overlies the Columbia River Basalt Group. In the 100-FR-3 OU and vicinity, the Ringold Formation consists of fluvial-lacustrine-derived (stream/lake) sediments that range from non-indurated to semi-indurated (loose to semi-hardened) clay, silt, fine- to coarse-grained sand, and pebble- to cobble-size gravel. These sediments are subdivided into five facies associations, which are defined based on lithology, petrology, stratification, and pedogenic alteration (DOE/RL-2008-46). Two Ringold Formation units, Unit E and the RUM, have been defined within the 100-FR-3 OU.

The Ringold Formation is estimated to be approximately 120 m (394 ft) thick beneath the 100-FR-3 OU based on data from one deep borehole, well 699-80-43P, located approximately 2.8 km (1.7 mi) west of the 100-F Area. The Hanford/Ringold contact surface ranges in depth from less than 8.9 m (29 ft) below ground surface (bgs) to over 22 m (72 ft) bgs. The oldest Ringold Formation units are composed of thick sequences of paleosol (soils) and overbank sediment (silt and clay), interspersed with laterally discontinuous coarse-grained sediments (DOE/RL-93-37, *Limited Field Investigation Report for the 100-BC-5 Operable Unit*). The uppermost fine-grained unit, typically referred to as the RUM, forms the base of the unconfined aquifer system within the OU. The RUM (including the lower, fine-grained Ringold Formation sediment) is up to 120 m (394 ft) thick at the 100-FR-3 OU (at well 699-80-43P).

The Ringold Unit E is composed of unconsolidated to slightly indurated, fluvially deposited, silty-sandy gravel and typically overlies the RUM surface; however, Unit E has been identified in only a few boreholes in the 100-FR-3 OU (Table 3-1) and appears limited in extent. Previous reports indicate that the Ringold Unit E is not present beneath the 100-F Area (e.g., WHC-SD-EN-TI-023 and WHC-SD-EN-TI-221). Differentiating the Ringold Unit E from the overlying Hanford formation gravel is difficult due to a lack of hydrogeologic characterization data, and information regarding the thicknesses of the Ringold Unit E and the RUM is very limited. Table 3-1 presents available geologic contact information from wells drilled within the 100-FR-3 OU. Hanford formation gravel unconformably overlies the RUM or Unit E where it occurs (i.e., Hanford/Ringold contact) within the OU.

Hanford/Ringold Contact

The contact between Hanford formation and the Ringold Formation (Hanford/Ringold contact) is important because the hydraulic properties of the Hanford formation gravel-dominated sequence generally create more transmissive and permeable conditions than the more compacted and locally cemented Ringold Unit E and the low-permeability, deeper, fine-grained units (i.e., the RUM). The Hanford/Ringold contact can affect contaminant transport in the vadose zone and groundwater. The Hanford/Ringold contact surface often occurs as buried paleo-flood and/or ancestral Columbia River channels, which, if occurring below the water table, can become preferential pathways for contaminated groundwater to migrate to the Columbia River (PNNL-14702). In some areas (e.g., near the 100-H Area, the Horn), the Hanford formation directly overlies the RUM, creating a more direct and relatively shallow contaminant flow path in the saturated Hanford sediment.

Within the 100-FR-3 OU, the Hanford formation also directly overlies the RUM, but some data suggest that residual ridges of Ringold Unit E persist locally between the Hanford formation and the RUM. However, as noted earlier, it is often difficult to differentiate the Hanford formation from the Ringold Unit E because both are gravel-dominated sediment sequences. Additionally, only a few deep boreholes were drilled and have the hydrogeologic descriptive results necessary to adequately characterize the interval. The units are differentiated based on characteristics such as a basalt clast content, gravel content, coloration, and cementation. The Hanford formation is typically less cemented than the Ringold Formation and has greater basalt gravel content, but the variety of drilling methods used can disrupt the integrity of these characteristics. Unconsolidated boulder gravel in the upper 6 to 15 m (20 to 50 ft) demonstrates the high-energy depositional environment created during the Missoula paleo-floods (Hanford formation). These deposits are difficult to penetrate by drilling methods (WHC-SD-EN-TI-221).

Hydrogeologic Surface (Structure) Maps

At the 100-FR-3 OU, the water table is situated in the Hanford formation. The unconfined aquifer that is contained primarily within the saturated Hanford formation (and possible localized remnants of Ringold Unit E) is the most significant unit for groundwater contaminant migration (Figures 3-24, 3-25, and 3-26). Groundwater and possibly contaminant movement may be slower in areas where residual remnants of Ringold Unit E sediment are present. To date, no distinct preferential flow paths have been defined in the 100-FR-3 OU.

The surface of the low-permeability RUM defines the base of the unconfined aquifer in the 100-FR-3 OU (Figure 3-26). The unconfined aquifer (interval above the RUM) is relatively thin in this region of the 100 Areas and ranges in thickness from less than 1 m (3 ft) near the upgradient west-southwestern region of the OU to more than 12 m (39 ft) downgradient in the southeastern portion of the OU (Figure 3-27). The RUM surface elevation ranges from over 118 m (387 ft) near the western upgradient region of the OU to less than 100 m (328 ft) in the southeastern portion of the OU adjacent to the river. The surface of the RUM has troughs and ridges (highs and lows) that roughly parallel the Columbia River and likely reflect ancestral Columbia River channels eroded into the RUM and subsequently abandoned during lateral migration beneath the 100-F Area. The base of the Ringold Formation and the base of the suprabasalt aquifer system are defined at the top of basalt, which is measured at approximately 134 m (440 ft) bgs in well 699-80-43P.

Within the unconfined aquifer, groundwater flows from regions of higher head west of the 100-F Area, toward the Columbia River, exhibiting an average hydraulic gradient of about 0.0012. Near the Columbia River, the unconfined aquifer is influenced by seasonal and diurnal changes in river stage that create river bank storage and localized groundwater flow reversals. Within the 100-F Area, groundwater flow is generally more or less perpendicular to (and from) the Columbia River. However, south of the 100-F Area, water-level mapping indicates that groundwater flow changes to a more southeasterly direction almost parallel to the Columbia River at that section. Figure 3-26 illustrates the estimated truncation of the RUM in the Columbia River based on river bed bathymetry (USGS, 2008, *Discharge and River Stage Data for the Columbia River Downstream of Priest Rapids Dam*). The extent along the 100-F Area where this RUM surface truncation occurs coincides with the region where groundwater flow is more or less toward the river (Figure 3-23). South of this region, (1) the RUM surface drops in elevation significantly to levels below the bottom of the river (Figure 3-26), and (2) the water table gradient in this region dramatically flattens (Figure 3-23). These features and data suggest that groundwater may be highly influenced by preferential flow within highly permeable, Hanford filled paleo-channels or features that parallel the river, or through direct influence by the river where the RUM does not obstruct groundwater/river water interaction . These affects have not been studied at 100-F Area but most likely do influence the movement of contaminants (primarily tritium, nitrate, and strontium-90) in groundwater that moves into this southeastern region of 100-F Area and ultimately into the Columbia River.

The Ringold Formation units beneath the RUM form confined to semiconfined conditions (aquitard) within the lower suprabasalt aquifer. The transmissivity of these older Ringold units is assumed to be lower than that of the upper unconfined aquifer based on comparative data from other areas.

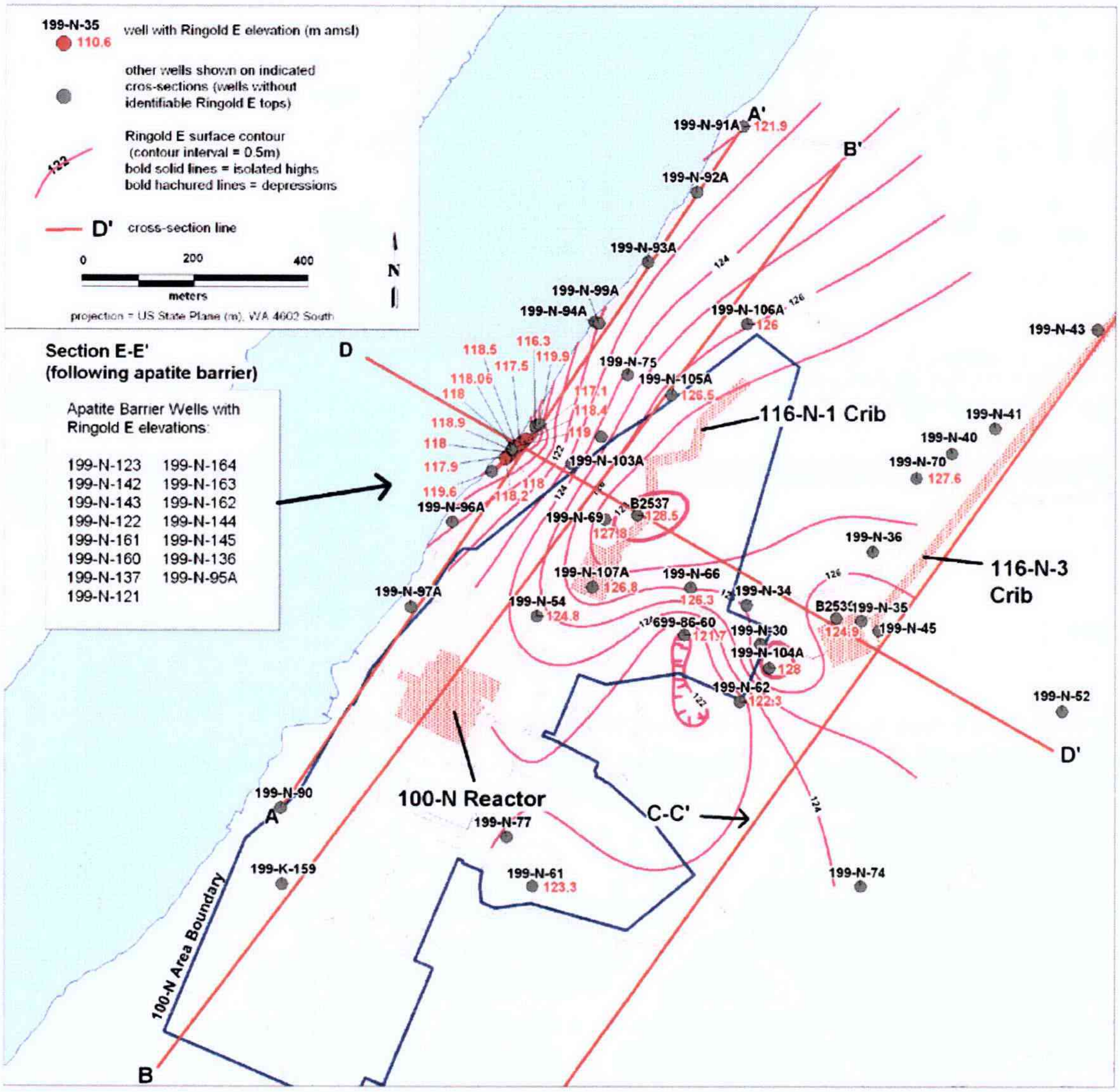


Figure 3-16. Location of Cross-Sections within the 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

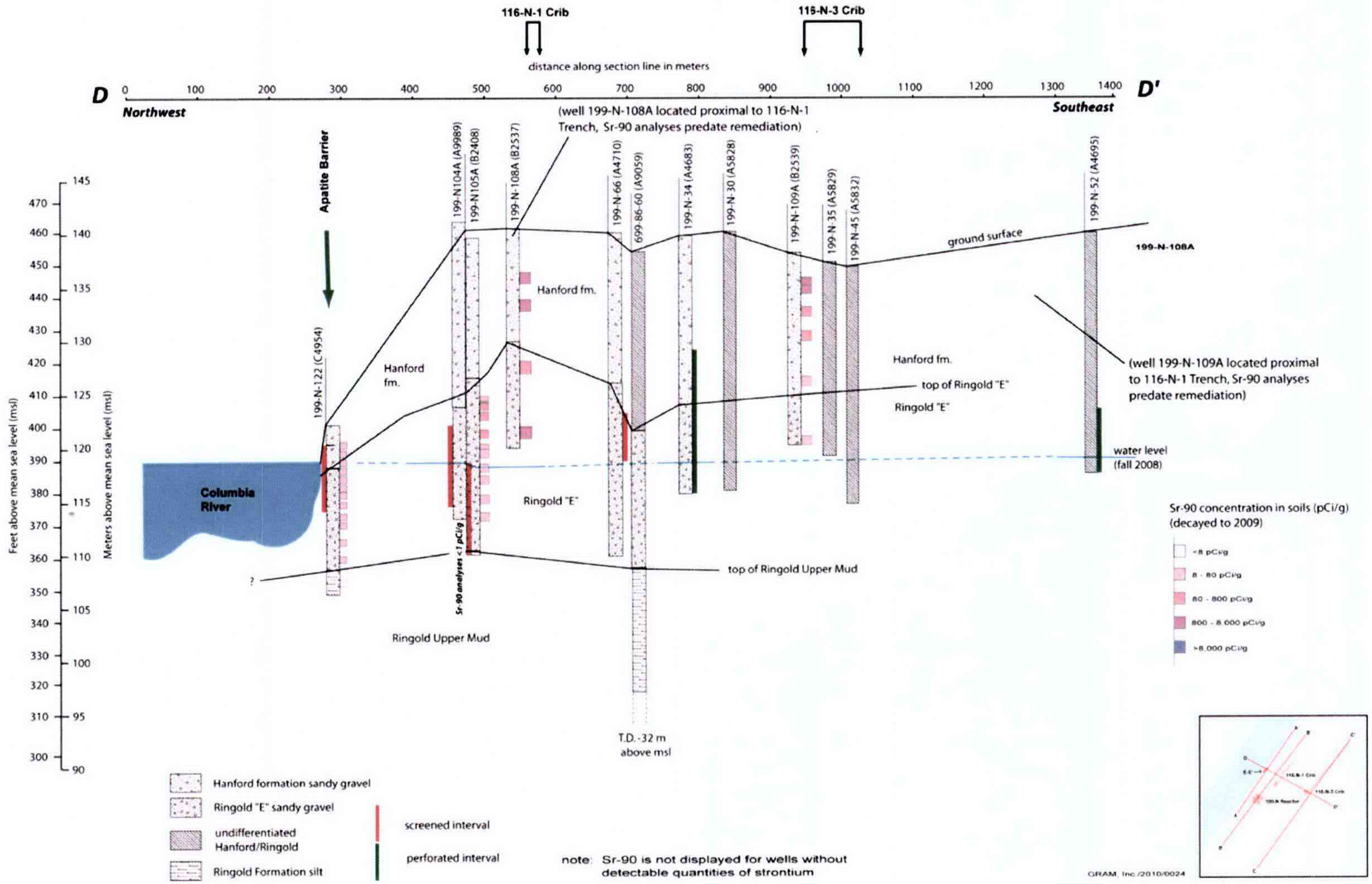


Figure 3-17. Hydrogeologic Cross-Section D-D', 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

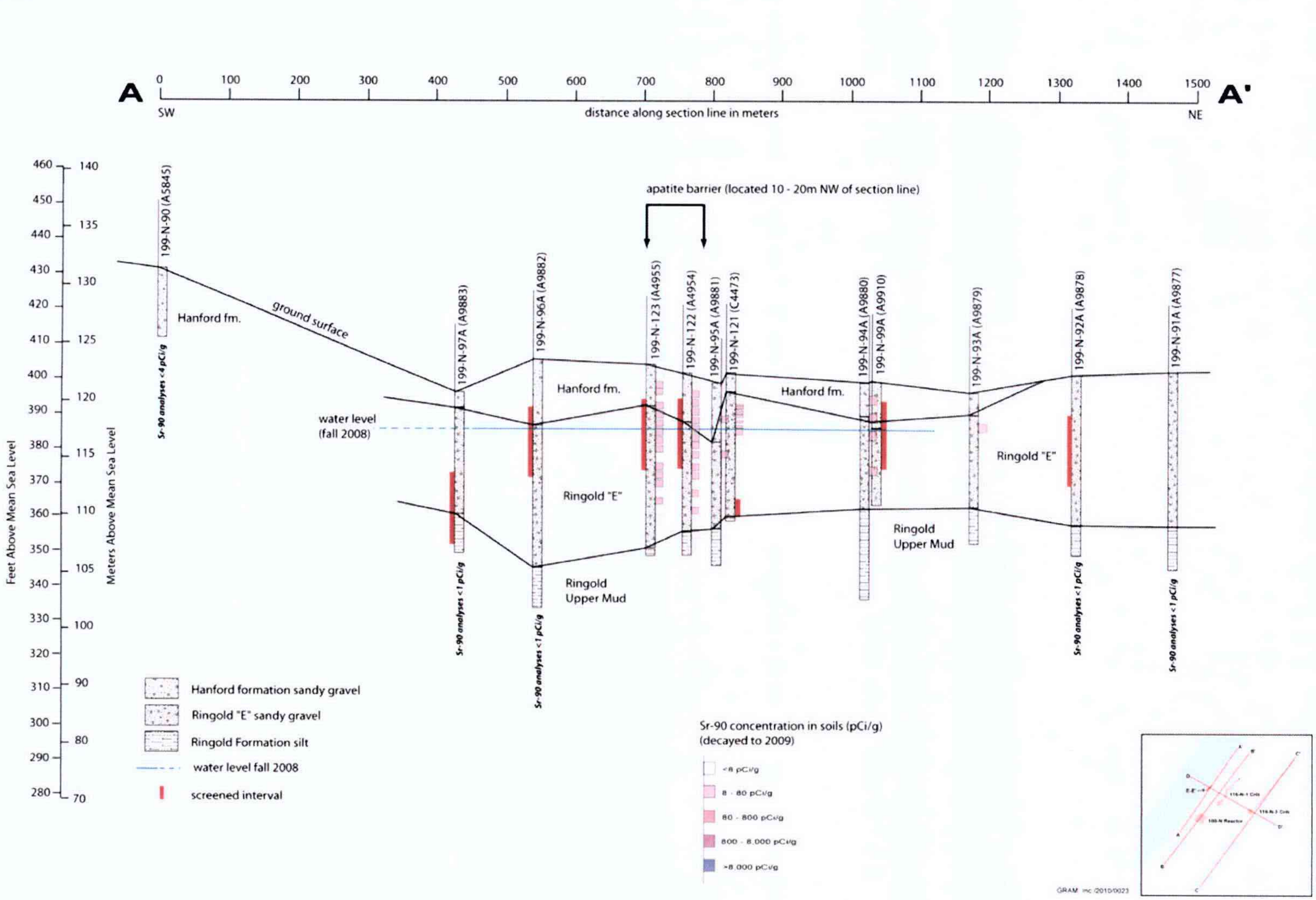


Figure 3-18. Hydrogeologic Cross-Section A-A', 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

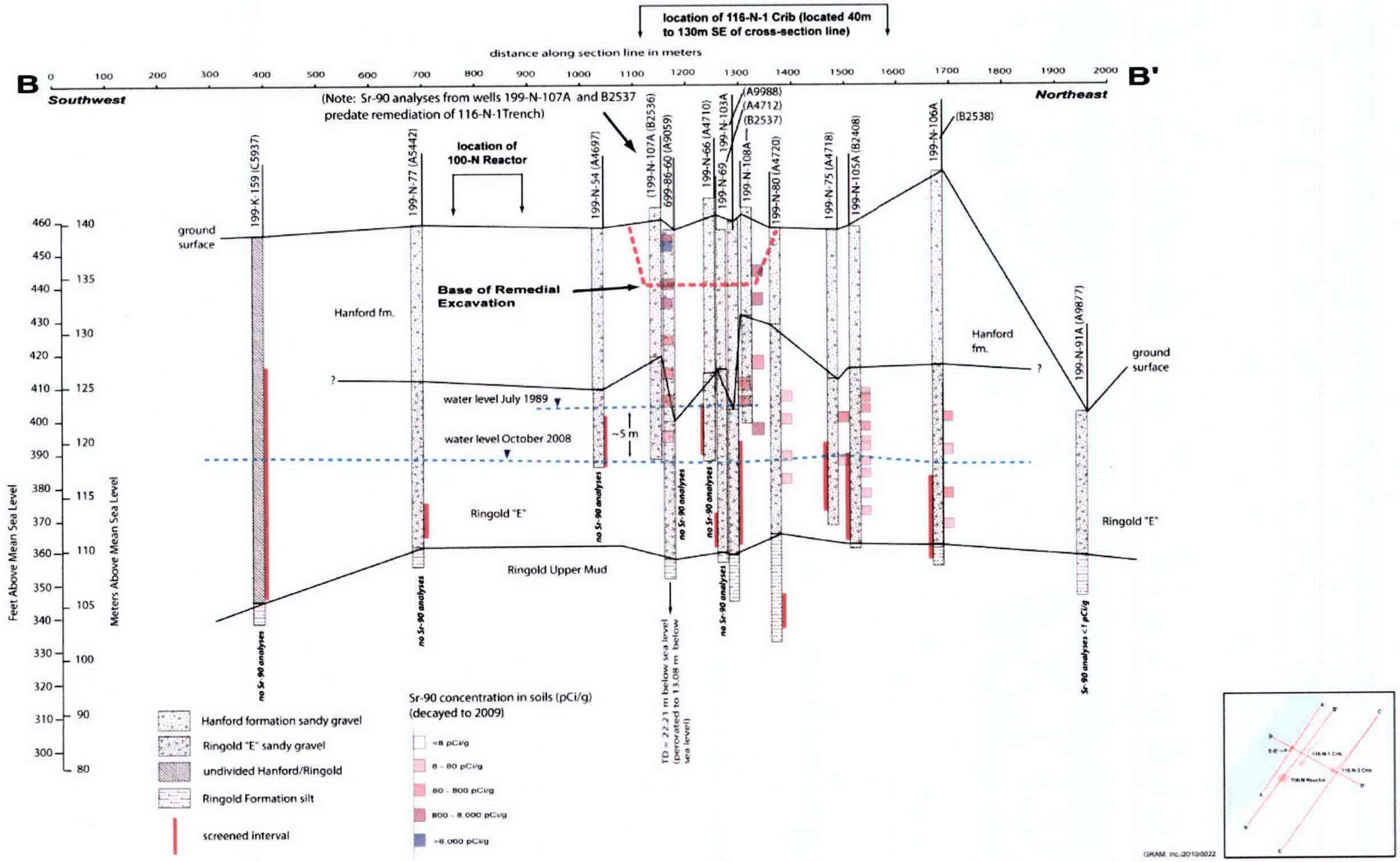


Figure 3-19. Hydrogeologic Cross-Section B-B', 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

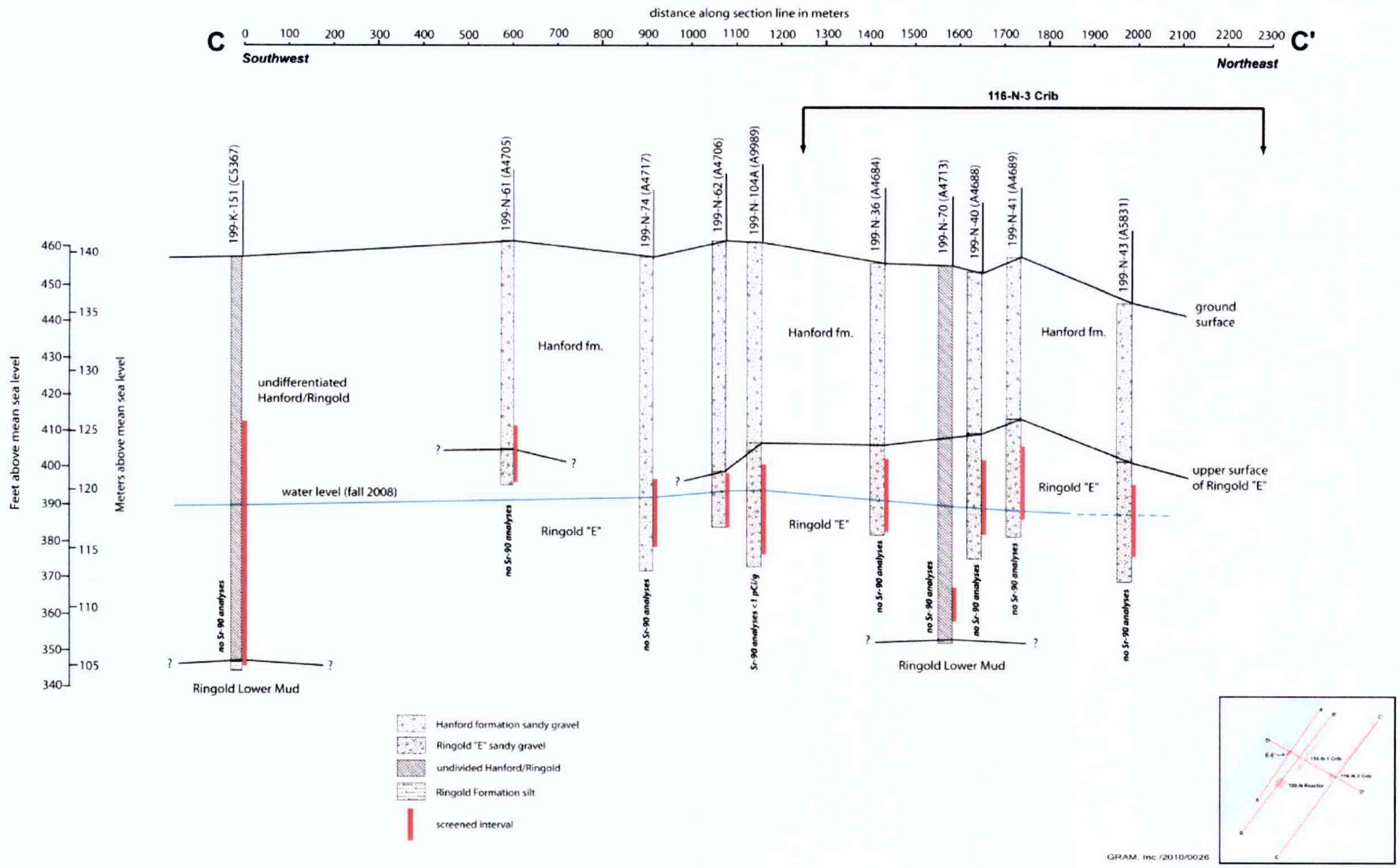


Figure 3-20. Hydrogeologic Cross-Section C-C', 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

Table 3-4. Geologic Data for the 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

Well Name	Well ID	Hanford Area	Well Type	Well Status	Total Depth (ft)	Disc Z Elev. (m)	Other Elev. (m)	Depth to Hanford/Ringold Contact (Ringold Unit E) (ft)	Elev. Ringold Unit E (m)	Depth to RUM (ft)	Elev. RUM (m)	Depth to Basalt (ft)	Comments
199-N-104A	A9889	100-N	Monitoring well	In use	91.5	141.34	N/A	57	128.0	N/A	N/A	N/A	Well did not reach RUM.
199-N-107A	B2536	100-N	Monitoring well	Decommissioned	76	N/A	141.26	44	127.8	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-136	C5042	100-N	Monitoring well	In use	25.8	N/A	122.06	12	118.4	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-137	C5043	100-N	Monitoring well	In use	25.8	N/A	122.00	16	117.1	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-142	C5048	100-N	Monitoring well	In use	25.5	N/A	122.20	14	117.9	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-143	C5049	100-N	Monitoring well	In use	25.8	N/A	122.26	14	118.0	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-144	C5050	100-N	Monitoring well	In use	25.7	N/A	122.25	14	118.0	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-145	C5051	100-N	Monitoring well	In use	25.7	N/A	122.08	10	119.0	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-160	C6178	100-N	Apatite barrier injection well	In use	26	N/A	122.08	15	117.5	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-161	C6179	100-N	Apatite barrier injection well	In use	25.2	N/A	122.13	12	118.5	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-162	C6180	100-N	Apatite barrier injection well	In use	26	N/A	122.24	11	118.9	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-163	C6181	100-N	Apatite barrier injection well	In use	25.9	N/A	122.22	14	118.0	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-164	C6182	100-N	Apatite barrier injection well	In use	25.4	N/A	122.18	13	118.2	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-54	A4697	100-N	Monitoring well	Decommissioned	73	139.77	N/A	49	124.8	N/A	N/A	N/A	Well did not reach RUM.
199-N-61	A4705	100-N	Monitoring well	Candidate for decommissioning	78.5	141.30	N/A	59	123.3	N/A	N/A	N/A	Well did not reach RUM.
199-N-62	A4706	100-N	Monitoring well	In use	78.5	141.82	N/A	64	122.3	N/A	N/A	N/A	Well did not reach RUM.
199-N-66	A4710	100-N	Monitoring well	In use	80	142.42	N/A	53	126.3	N/A	N/A	N/A	Well did not reach RUM.
699-86-60	A9059	100-N	Monitoring well	Decommissioned	530	N/A	138.41	55	121.7	96.0	109.2	515	Surface elevation = top of casing; survey elevation less 3 ft of assumed stickup.

Table 3-4. Geologic Data for the 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

Well Name	Well ID	Hanford Area	Well Type	Well Status	Total Depth (ft)	Disc Z Elev. (m)	Other Elev. (m)	Depth to Hanford/Ringold Contact (Ringold Unit E) (ft)	Elev. Ringold Unit E (m)	Depth to RUM (ft)	Elev. RUM (m)	Depth to Basalt (ft)	Comments
199-N-108A	B2537	100-N	Monitoring well	Decommissioned	72.5	N/A	141.26	42	128.5	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
B2539	B2539	100-N	Monitoring well	Decommissioned	64.5	N/A	138.34	44	124.9	N/A	N/A	N/A	Surface elevation from well construction summary report; well did not reach RUM.
199-N-105A	B2408	100-N	Monitoring well	In use	96	139.62	N/A	43.0	126.5	96.0	110.4	N/A	
199-N-106A	B2538	100-N	Monitoring well	In use	121.5	144.63	N/A	58.0	126.0	119.0	108.4	N/A	
199-N-121	C4473	100-N	Monitoring well	In use	42.5	122.38	N/A	8.0	119.9	41.0	109.9	N/A	
199-N-122	C4954	100-N	Monitoring well	In use	48	122.33	N/A	14.0	118.1	44.5	108.8	N/A	
199-N-123	C4955	100-N	Monitoring well	In use	54	123.10	N/A	11.5	119.6	52.8	107.2	N/A	
199-N-69	A4712	100-N	Monitoring well	In use	104	140.61	N/A	42.0	127.8	101.0	109.8	N/A	
199-N-70	A4713	100-N	Monitoring well	In use	104.4	138.91	N/A	37.0	127.6	104.0	107.2	N/A	
199-N-91A	A9877	100-N	Monitoring well	Decommissioned	59	122.55	N/A	2.0	121.9	44.0	109.1	N/A	
199-N-95A	A9881	100-N	Monitoring well	Decommissioned	49	N/A	120.58	14.0	116.3	38.5	108.9	N/A	Elevation from well summary sheet; assumed to be ground surface.
199-N-77	A5442	100-N	Monitoring well	In use	103	139.94	N/A	N/A	N/A	102.0	110.4	N/A	
199-N-80	A4720	100-N	Monitoring well	In use	126	139.61	N/A	N/A	N/A	98.0	109.7	N/A	
199-N-92A	A9878	100-N	Monitoring well	In use	51.5	122.10	N/A	N/A	N/A	42.0	109.2	N/A	
199-N-93A	A9879	100-N	Monitoring well	Decommissioned	43	120.79	N/A	N/A	N/A	33.1	110.7	N/A	
199-N-94A	A9880	100-N	Monitoring well	Decommissioned	33	121.60	N/A	N/A	N/A	36.5	110.5	N/A	
199-N-96A	A9882	100-N	Monitoring well	In use	71	123.64	N/A	N/A	N/A	60.0	105.4	N/A	
199-N-103A	A9988	100-N	Monitoring well	In use	105	140.32	N/A	N/A	N/A	102.0	109.2	N/A	
199-N-90	A5845	100-N	Monitoring well	Decommissioned	19.8	131.40	N/A	N/A	N/A	N/A	N/A	N/A	All sediments = Hanford formation; well did not reach RUM.

Table 3-4. Geologic Data for the 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

Well Name	Well ID	Hanford Area	Well Type	Well Status	Total Depth (ft)	Disc Z Elev. (m)	Other Elev. (m)	Depth to Hanford/Ringold Contact (Ringold Unit E) (ft)	Elev. Ringold Unit E (m)	Depth to RUM (ft)	Elev. RUM (m)	Depth to Basalt (ft)	Comments
199-N-97A	A9883	100-N	Monitoring well	Decommissioned	46	120.845	N/A	5	119.3	35	110.2	N/A	
199-N-95A	A9881	100-N	Monitoring well	Decommissioned	49	N/A	120.579	14	116.3	38.5	108.8	N/A	Elevation from well summary sheet, assumed to be ground surface.
199-K-159	C5937	100-K	Monitoring well	In use	117	138.945	N/A	N/A	N/A	110	105.4	N/A	
199-N-75	A4718	100-N	Monitoring well	In use	89.6	139.325	N/A	45	125.6	N/A	N/A	N/A	Well did not reach RUM.
199-K-151	C5367	100-K	Monitoring well	In use	118.8	139.813	N/A	N/A	N/A	118	102.847	N/A	
199-N-74	A4717	100-N	Monitoring well	In use	84	139.44	N/A	N/A	N/A	N/A	N/A	N/A	Log indicates Hanford formation to total depth; well did not reach RUM.
199-N-36	A4684	100-N	Monitoring well	Decommissioned	75	N/A	140.075	50	125.0	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 2.6 ft of stickup; well did not reach RUM.
199-N-40	A4688	100-N	Monitoring well	Decommissioned	80	N/A	139.67	45	126.0	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 2 ft of stickup; well did not reach RUM.
199-N-41	A4689	100-N	Monitoring well	In use	78	N/A	139.895	45	126.2	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 2.5 ft of stickup; well did not reach RUM.
199-N-43	A5831	100-N	Monitoring well	Decommissioned	80	N/A	137.133	45	123.4	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 3 ft of assumed stickup; well did not reach RUM.
199-N-34	A4683	100-N	Monitoring well	In use	78	N/A	140.365	50	125.1	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 3 ft of assumed stickup; well did not reach RUM.
199-N-30	A5828	100-N	Monitoring well	Decommissioned	79	N/A	139.711	N/A	N/A	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 3 ft of assumed stickup; well did not reach RUM.
199-N-35	A5829	100-N	Monitoring well	Decommissioned	64	N/A	137.239	50	122	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 3 ft of assumed stickup; well did not reach RUM.
199-N-45	A5832	100-N	Monitoring well	Decommissioned	73	N/A	138.128	55	121.364	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 3 ft of assumed stickup; well did not reach RUM.
199-N-52	A4695	100-N	Monitoring well	In use	76	N/A	141.904	N/A	N/A	N/A	N/A	N/A	Surface elevation = top of casing; survey elevation less 2 ft of stickup; well did not reach RUM.

Table 3-4. Geologic Data for the 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

Well Name	Well ID	Hanford Area	Well Type	Well Status	Total Depth (ft)	Disc Z Elev. (m)	Other Elev. (m)	Depth to Hanford/Ringold Contact (Ringold Unit E) (ft)	Elev. Ringold Unit E (m)	Depth to RUM (ft)	Elev. RUM (m)	Depth to Basalt (ft)	Comments
199-N-138	C5044	100-N	Monitoring well	In use	26.2	123.120	N/A	N/A	N/A	N/A	N/A	N/A	Well did not reach RUM.
199-N-139	C5045	100-N	Monitoring well	In use	25.7	122.781	N/A	N/A	N/A	N/A	N/A	N/A	Well did not reach RUM.
199-N-140	C5046	100-N	Monitoring well	In use	25.7	122.461	N/A	N/A	N/A	N/A	N/A	N/A	Well did not reach RUM.
199-N-146	C5052	100-N	Monitoring well	In use	25.5	122.411	N/A	N/A	N/A	N/A	N/A	N/A	Well did not reach RUM.
199-N-141	C5047	100-N	Monitoring well	In use	25.8	122.260	N/A	N/A	N/A	N/A	N/A	N/A	Well did not reach RUM.
199-N-159	C6177	100-N	Apatite barrier injection well	In use	25	122.043	N/A	N/A	N/A	N/A	N/A	N/A	Well did not reach RUM.
199-N-147	C5116	100-N	Monitoring well	In use	25.8	122.221	N/A	N/A	N/A	N/A	N/A	N/A	Well did not reach RUM.

ID = identification
N/A = not available
RUM = Ringold upper mud (unit)

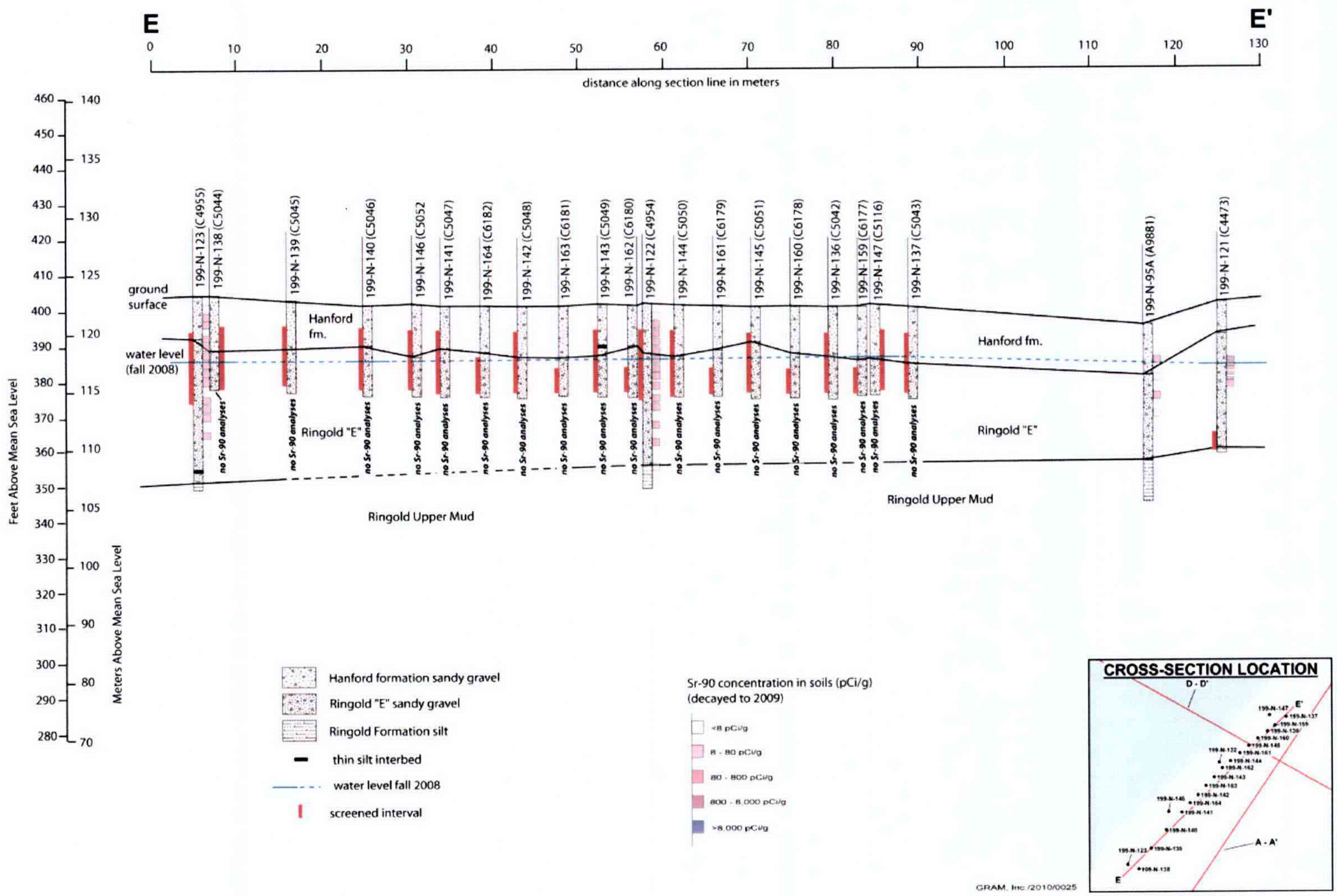


Figure 3-21. Hydrogeologic Cross-Section E-E', 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

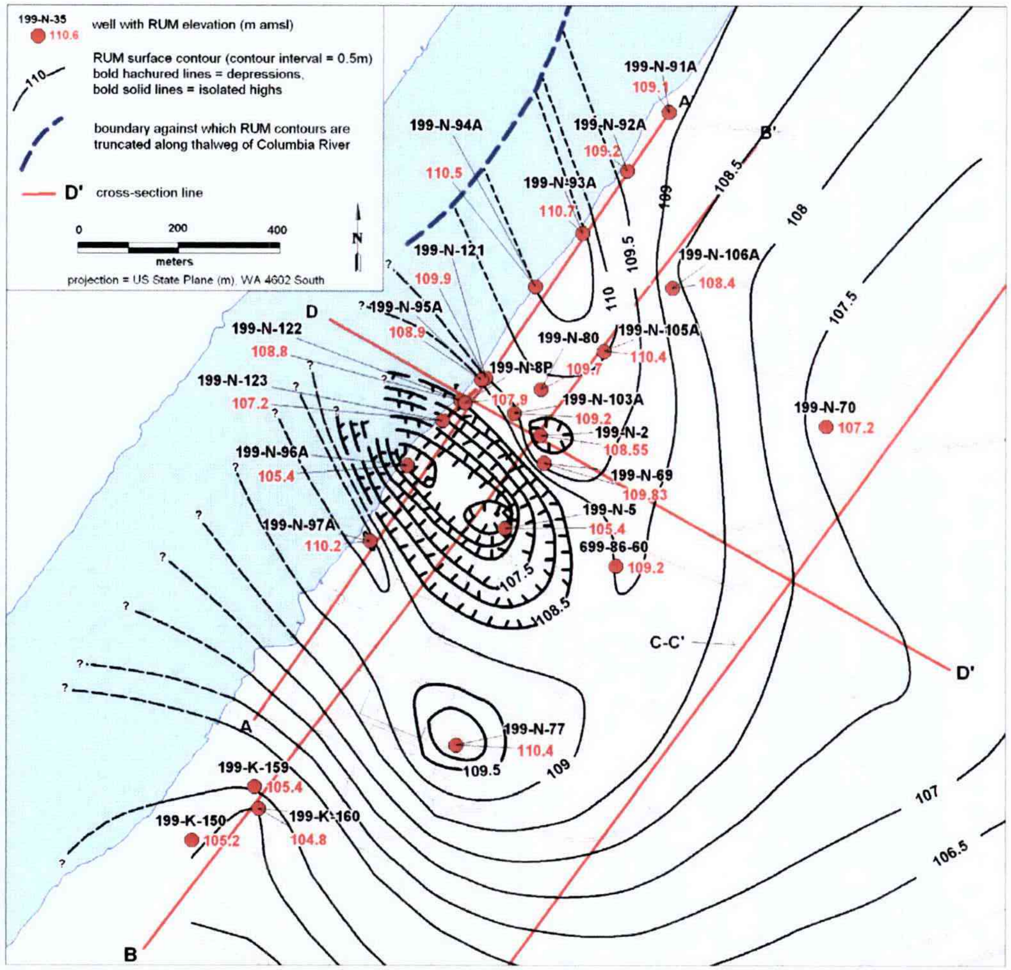


Figure 3-22. Hydrogeologic Surface (Structure) Map of the Ringold Upper Mud Unit, 100-NR-2 Groundwater OU (after SGW-47786, Rev. 0)

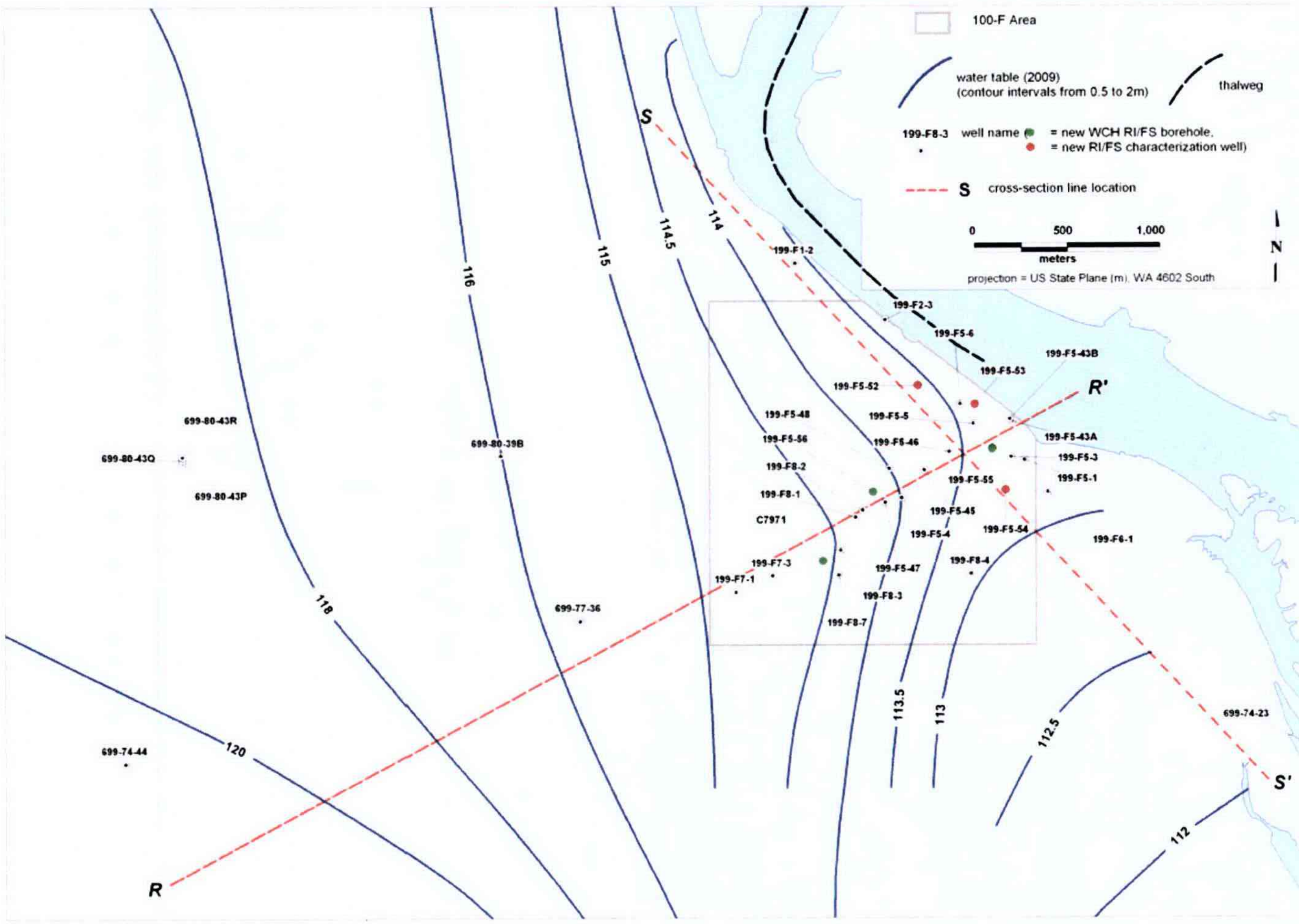


Figure 3-23. Location of Cross Section within the 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

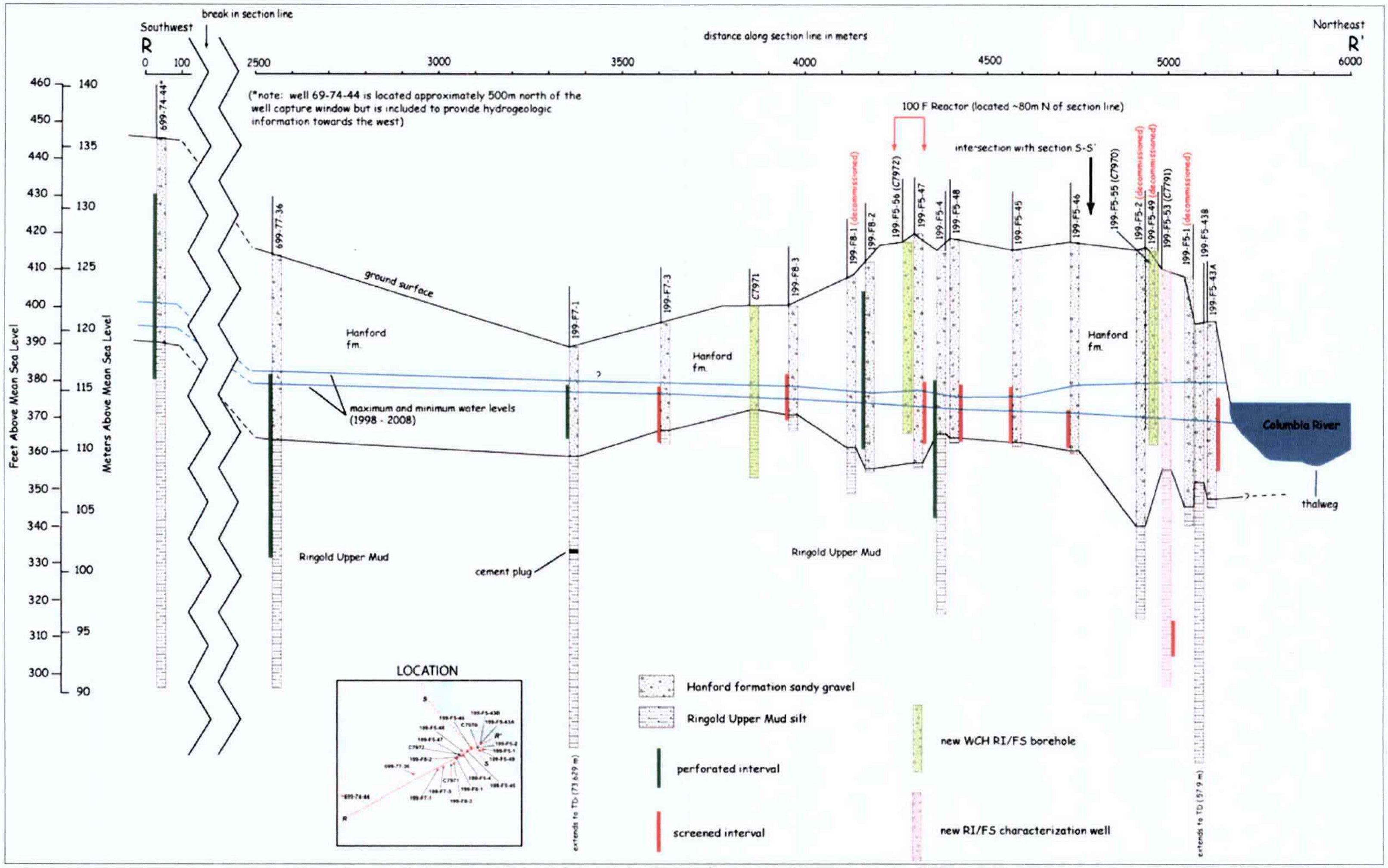


Figure 3-24. Hydrogeologic Cross-Section R-R', 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

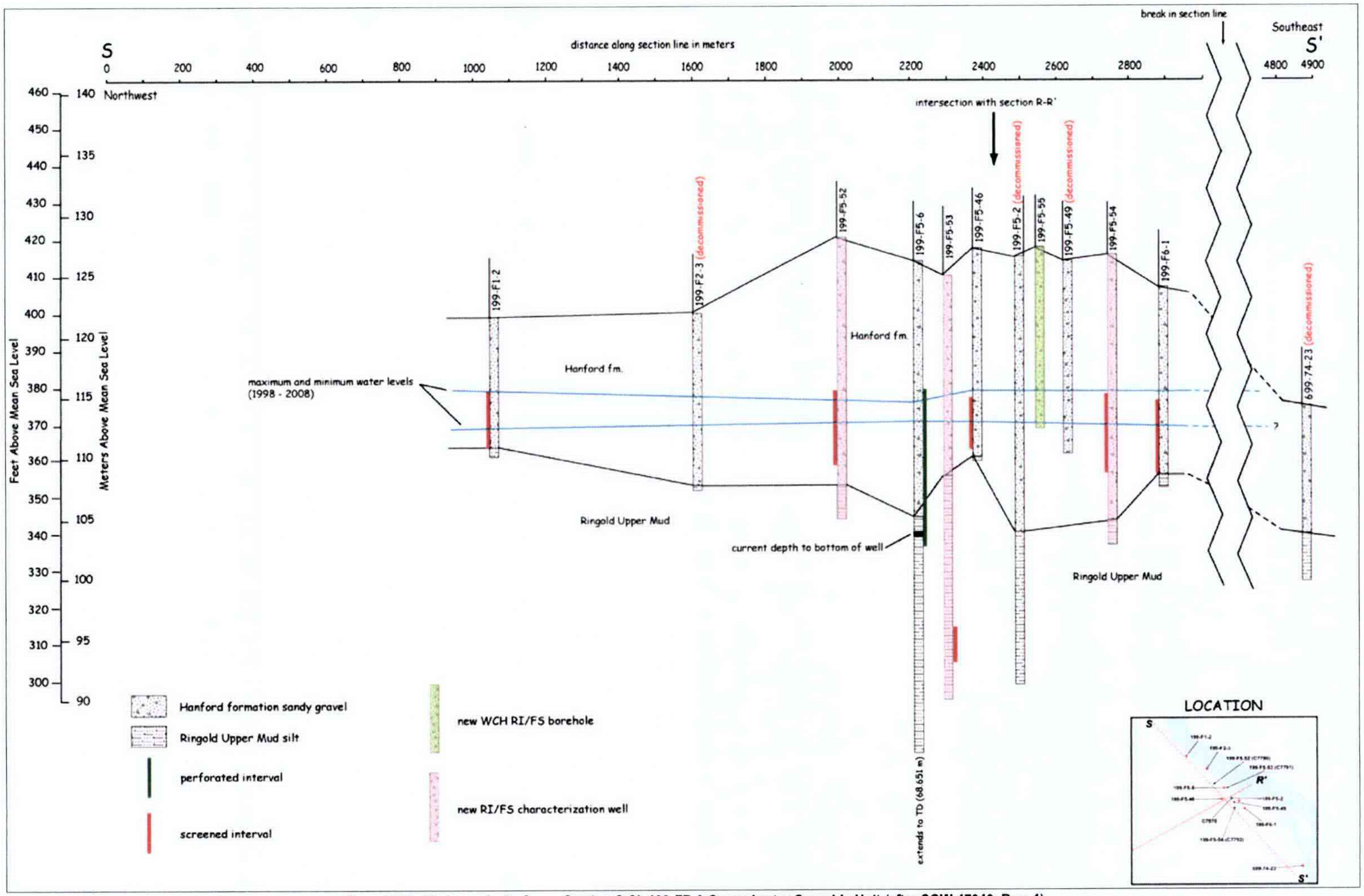


Figure 3-25. Hydrogeologic Cross-Section S-S', 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

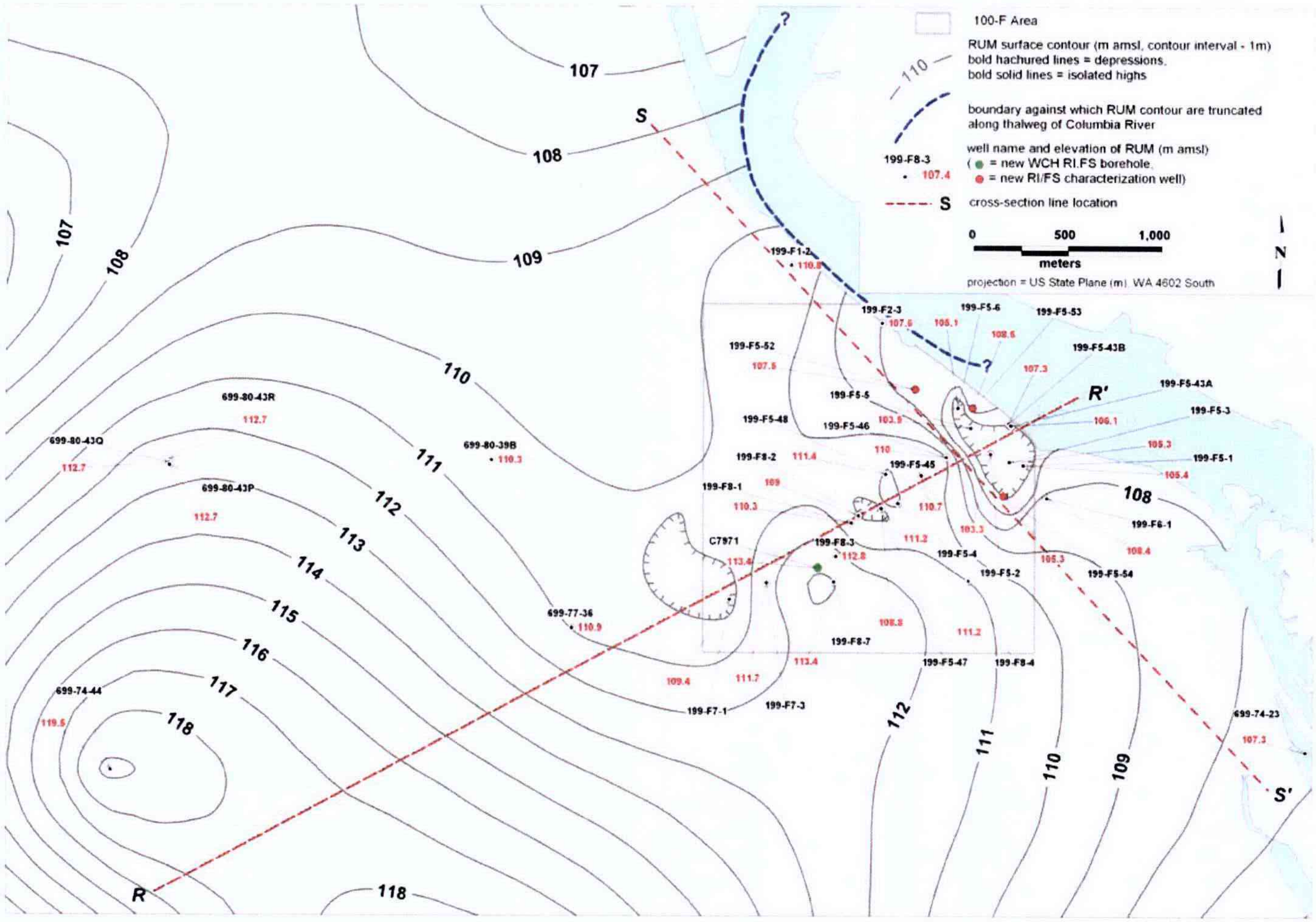


Figure 3-26. Hydrogeologic Surface (Structure) Map of the Ringold Formation Upper Mud, 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

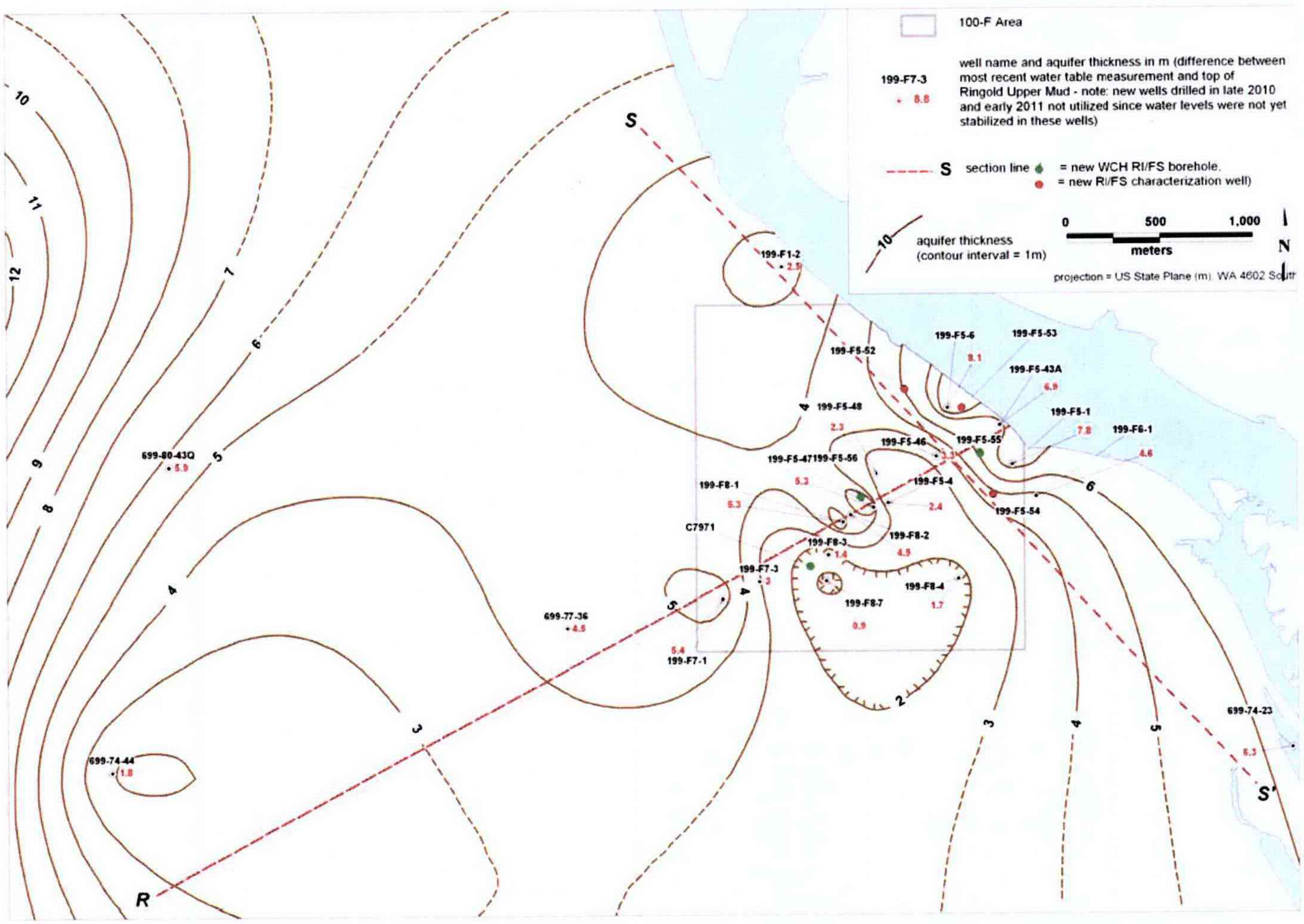


Figure 3-27. Uppermost Unconfined Aquifer Thickness Map, 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

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Table 3-5. Geologic Data for the 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

Well Name	Easting	Northing	Surface Elev. (m)	Hf/RE Elev. (m)	RUM Elev. (m)	Elevation Control	Elevation Source	RUM Depth Data Source	Notes
199-F1-2	580011	148805.3	121.47	--	110.8	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Ringold unit E not present.
199-F2-3	580496.2	148497.8	121.84	--	107.6	TOC; 3 ft stickup (assumed)	Horizontal + vertical survey data	Well summary sheet, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F5-1	581250.1	147736.9	124.27	--	105.4	TOC; 1.0 ft stickup	Well construction summary	Well summary sheet, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F5-2	581076.2	147799.5	126.47	--	103.3	TOC; 1.4 ft stickup	Well construction summary	Well summary sheet, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F5-4	580583.2	147533.7	126.47	--	111.2	TOC; 0.55 ft stickup	Well construction summary	Well summary sheet, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F5-43A	581183.9	147948.1	120.61	--	106.1	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F5-46	580841.3	147781.5	127.19		110.0	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F5-47	580495.5	147508.5	127.84		108.8	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F5-48	580517.6	147690.1	127.29	121.8	111.4	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Possible remnant of Ringold unit E.

Table 3-5. Geologic Data for the 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

Well Name	Easting	Northing	Surface Elev. (m)	Hf/RE Elev. (m)	RUM Elev. (m)	Elevation Control	Elevation Source	RUM Depth Data Source	Notes
199-F5-49	581133.2	147705	125.99	120.5	110.1	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Possible remnant of Ringold unit E.
199-F5-52	***580672.81***	***148143.82***	***127.62***	--	***107.5***	***Disc Z***	--	***Borehole log, GRAM, Inc. interpretation***	***Ringold unit E not present.***
199-F5-53	***580978.5***	***148042.5***	***125.11***	--	***108.5***	***Disc Z***	--	***Borehole log, GRAM, Inc. interpretation***	***Ringold unit E not present.***
199-F5-54	***581145.3***	***147576.2***	***126.62***	--	***105.3***	***Disc Z***	--	***Borehole log, GRAM, Inc. interpretation***	***Ringold unit E not present.***
199-F5-55	***581076.1***	***147797.6***	***126.81***	--	--	***Ground surface; Disc Z***		***Borehole log, GRAM, Inc. interpretation***	***Hanford formation/Ringold unit E not identified in log., borehole did not reach RUM***
199-F5-56	***580430***	***147565***	***127.22***	--	--	***Ground surface; Disc Z***		***Borehole log, GRAM, Inc. interpretation***	***Hanford formation/Ringold unit E not identified in log., borehole did not reach RUM***
199-F5-6	580901.7	148042	126.12	--	105.1	TOC; 3 ft stickup (assumed)	Assumed stickup	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F6-1	581375.9	147564.5	123.6	--	108.4	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F7-1	579687.2	147022.4	118.59	--	109.4	TOC; 2.5 ft stickup	Well construction summary	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F7-3	579884.7	147112.5	120.49	115.3	111.6	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Possible remnant of Ringold unit E.

Table 3-5. Geologic Data for the 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

Well Name	Easting	Northing	Surface Elev. (m)	Hf/RE Elev. (m)	RUM Elev. (m)	Elevation Control	Elevation Source	RUM Depth Data Source	Notes
199-F8-1	580335.3	147430.5	124.06	116.4	110.3	TOC; 2.2 ft stickup	Well construction summary	Borehole log, GRAM, Inc. interpretation	Possible remnant of Ringold unit E.
199-F8-2	580373.9	147468.5	125.46	--	109.2	TOC; 2.5 ft stickup	Well construction summary	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F8-3	580254	147253.4	121.95	--	112.8	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F8-4	580958.5	147123.5	125.37	--	111.2	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
199-F8-7	580242.9	147116.7	123.17	--	113.4	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
699-74-23	582756.4	146203.2	115.39	--	107.8	TOC; 1.4 ft stickup	Horizontal + vertical survey data	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
699-74-44	576393.1	146098.8	136.28	--	119.5	TOC; 1.4 ft stickup	Well construction summary	Williams Well log	Hanford formation/Ringold unit E not identified in log.
699-74-48	575237.7	146037.7	148.88	--	111.1	TOC; 1.75 ft stickup	Well construction summary	Williams Well log	Hanford formation/Ringold unit E not identified in log.
699-77-36	578847.2	146868.9	126.09	--	110.9	TOC; 1.9 ft stickup	Well construction summary	Well summary sheet, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
699-77-54	573386	146854.8	146.92	118.0	100.6	TOC; 1.4 ft stickup	Well construction summary	Well summary sheet, GRAM, Inc. interpretation	--

Table 3-5. Geologic Data for the 100-FR-3 Groundwater Operable Unit (after SGW-47040, Rev. 1)

Well Name	Easting	Northing	Surface Elev. (m)	Hf/RE Elev. (m)	RUM Elev. (m)	Elevation Control	Elevation Source	RUM Depth Data Source	Notes
699-80-43P	576703.9	147729.9	126.68	--	112.7	TOC; 1.5 ft stickup	Well construction summary	Williams well log	--
699-80-43Q	576703.2	147745	126.41	--	112.7	TOC; 1.5 ft stickup	Well construction summary	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
699-80-43R	576702.5	147760.3	126.46	--	112.7	TOC; 1.5 ft stickup	Well construction summary	Borehole log, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
699-80-43S	576701.9	147774.7	126.36	--	114.1	TOC; 1.5 ft stickup	Well construction summary	Borehole log, GRAM, Inc. interpretation	--
699-80-39B	578418.4	147763.3	123.45	--	110.3	TOC; 3 ft stickup (assumed)	Well construction summary	Well construction summary, GRAM, Inc. interpretation	Hanford formation/Ringold unit E not identified in log.
C7971	580158	147193	122.14	--	113.3	Disc Z	--	Borehole log, GRAM, Inc. interpretation	Ringold unit E not present.

Notes: Rows shown in bold and italic are new wells added per this update (revision).

Hf = Hanford formation

RE = Ringold Formation unit E

RUM = Ringold upper mud (unit)

TOC = top of casing

3.3 100 Area Vadose Zone

For the majority of contaminants, movement through the vadose zone is contingent upon dissolution in flowing water. The average thickness of the vadose zone in the reactor areas ranges from 6 m (19.7 ft) in the 100-F Area to more than 30 m (98 ft) in the 100-B/C Area, with the thickness in each reactor area varying slightly. During operations, groundwater mounding reduced the thickness of the vadose zone by 6 to 9 m (19.7 to 29.5 ft) directly under the retention basins or other LWDFs (PNNL-14702).

The hydrogeologic framework of the vadose zone is complex; however, locally within the 100 Areas, the vadose zone can be divided into two primary hydrostratigraphic units: (1) the gravel-dominated facies associated with the Hanford formation, and (2) the conglomeratic member of Wooded Island Unit E of the Ringold Formation (DOE/RL-2002-39; BHI-00917, *Conceptual Site Models for Groundwater Contamination at the 100-BC-5, 100-KR-4, 100-HR-3, and 100-FR-3 Operable Units*; WHC-SD-EN-EV-027; WHC-SD-EN-TI-132; WHC-SD-EN-TI-133; and WHC-SD-EN-TI-155, *Geology of the 100-K Area, Hanford Site, South-Central Washington*). The Ringold Formation makes up the lower portion of the vadose zone at the 100-K, 100-N, and the 100-D Areas; it is only partially present in the 100-B/C Area and absent in the 100-H and 100-F Areas. The Hanford formation extends from the surface to just above the water table when the Ringold Formation is present. The Hanford formation extends beneath the water table and makes up the unconfined aquifer in the 100-H and 100-F Areas.

The Ringold Unit E is a fluvially deposited, pebble-to-cobble gravel with a sandy matrix. The unit is characterized by complex interstratified beds and lenses of sand and gravel with low to moderate degrees of cementation. The gravel-dominated facies of the Hanford formation is generally composed of uncemented, clast-supported pebble, cobble, and boulder gravel with a poorly sorted silty sandy matrix and minor sand and silt interbeds or stringers. The Hanford formation occasionally exhibits an open-framework texture with little or no matrix. The clast size decreases in the lower portion of the Hanford formation. The Hanford formation is generally less cemented and more poorly sorted than the Ringold Formation and typically contains a higher percentage of angular basaltic detritus.

For most applications, flow rates through the vadose zone can be modeled using Richards' equation with gravity and capillary potential gradients providing the dominant forces. Chapter 4 provides a summary of 100 Area vadose zone hydraulic properties (i.e., soil moisture content versus capillary pressure, and unsaturated hydraulic conductivity versus moisture content relationships).

Although preferential pathways such as clastic dikes have been observed in the vadose zone beneath the 100 Areas (BHI-01103, *Clastic Injection Dikes of the Pasco Basin and Vicinity: Geologic Atlas Series*), this occurrence is fairly uncommon. The limited distribution and lack of vertical continuity of these pathways may render them insignificant as preferential routes for migration.

As previously discussed, the contact between Ringold Unit E and the Hanford formation is important because the saturated hydraulic conductivity for the gravel-dominated sequence of the Hanford formation is higher than the more compacted and locally cemented Ringold Unit E. In addition, varying groundwater-level responses and transport characteristics may occur where channels that are now filled with the Hanford formation have been scoured into the Ringold Unit E: such buried channels could become preferential pathways for contaminant migration when inundated during high river stage.

3.4 Events

Both natural and anthropogenic recharge events for various OUs are discussed in the following subsections. The discussion on natural recharge is common to the entire 100 Areas whereas the discussion on anthropogenic recharge is reactor area-specific.

3.4.1 Natural Recharge

The long-term, natural driving force for flow and transport through the vadose zone is precipitation that has infiltrated below the zone of evaporation and below the influence of plant roots. Such water eventually flows to the water table, carrying with it any dissolved contaminants. The actual fraction of precipitation that ultimately recharges the groundwater depends on the soil type and vegetation. In "*Variations in Recharge at the Hanford Site*" (Gee et al. 1992), evidence was presented from multiple experiments showing that measurable diffuse natural recharge occurs across the lower elevations of the Hanford Site, with rates ranging from near zero in undisturbed shrub-steppe plant communities to more than 100 mm/year beneath the nonvegetated graveled surfaces such as those existing in the 100 Areas.

The arid climate of the Hanford Site, with cool wet winters and dry hot summers, dictates that recharge potential is greatest in winter (Gee et al. 1992). During winter months, the amount of precipitation is the greatest and the evaporation potential is the lowest, therefore precipitation has the greatest chance to infiltrate into sediments. This type of recharge can occur as either diffuse or focused recharge. The contribution of each event is site- and event-dependent. Winter water runoff from the higher elevations over frozen ground, while infrequent, can be extensive (e.g., BNWL-SA-2574, *The Arid Lands Ecology Reserve at Pacific Northwest Laboratory, Richland, Washington*). In "*Springs and Streams in Shrub-Steppe Balance and Change in a Semi-Arid Terrestrial Ecosystem*" (Cushing and Vaughan 1988), it was indicated that runoff from higher elevations has a 3.8-year return period. Extensive water runoff does not appear prevalent between Highway 240 and the Columbia River based on the absence of geomorphic features (e.g., erosion rills and gullies). Undisturbed (natural) sites in the 100 Areas typically have gentle terrain and coarse soils that foster diffuse recharge. In contrast, at disturbed waste sites, localized ponding can give rise to focused flow. Observations confirm that local runoff does occur at waste sites when heavy rain or quick snowmelt occurs, and where the ground is frozen or compacted as a result of normal waste operations (e.g., PNL-SA-17633, *Simulating the Water Balance of an Arid Site*; PNNL-11463, *A Comprehensive Analysis of Contaminant Transport in the Vadose Zone Beneath Tank SX-109*).

Based on PNNL-14702, Table 3-6 provides the estimated natural recharge for the soil type and the vegetation scenario prevalent in the 100 Areas. These estimates have been derived from a suite of available field data and computer simulation results, including the following:

- "Chemical Estimates of Paleorecharge in the Pasco Basin: Evaluation of the Chloride Mass-Balance Technique" (Murphy et al. 1996)
- "Estimating Recharge Rates for a Groundwater Model Using GIS" (Fayer et al. 1999)
- PNL-10285, *Estimated Recharge Rates at the Hanford Site*
- *Using Chloride and Chlorine-36 as Soil-Water Tracers to Estimate Deep-Percolation at Selected Locations on the U.S. Department of Energy Hanford Site* (Prych 1998).

Table 3-6. Estimated Natural Recharge Rates for the 100 Areas

Soil Type (Area)	Estimated Recharge Rate (mm/yr)			
	No Vegetation	Cheatgrass	Young Shrub-Steppe	Shrub-Steppe
Ephrata sandy loam (100-B/C)	17	8.5	3.0	1.5
Burbank loamy sand (100-B/C)	53	26.5	6.0	3.0
Ephrata sandy loam (100-K)	17	8.5	3.0	1.5
Ephrata sandy loam (100-D)	17	8.5	3.0	1.5
Ephrata stony loam (100-D)	17	8.5	3.0	1.5
Burbank loamy sand (100-H)	53	26.5	6.0	3.5

Source: PNNL-14702, *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis.*

The soil type is identified in Table 3-6 using the soil map provided in *Soil Survey: Hanford Project in Benton County, Washington* (BNWL-243). Because of site operations, the soil and vegetation at many of the waste sites have been disturbed, which has resulted in an increase in recharge rates. Table 3-7 (based on PNNL-14702) provides the estimated recharge rates for disturbed conditions, as well as variability including ranges and standard deviation.

Table 3-7. Estimated Recharge Rates and Variation for Disturbed Conditions in the 100 Areas

Condition (Area)	Best Estimate (mm/yr)	Estimated Standard Deviation (mm/yr)	Minimum (mm/yr)	Maximum (mm/yr)
Ephrata stony loam, disturbed and with no vegetation (100-B/C)	17	8.5	8.5	34
Burbank loamy sand, disturbed and with no vegetation (100-B/C)	53	26.5	26.5	101
Ephrata sandy loam, disturbed and with no vegetation (100-K)	17	8.5	8.5	34
Ephrata sandy loam, disturbed and with no vegetation (100-D)	17	8.5	8.5	34
Ephrata stony loam, disturbed and with no vegetation (100-D)	17	8.5	8.5	34
Burbank loamy sand, disturbed and with no vegetation (100-H)	53	26.5	26.5	101

Source: PNNL-14702, *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis.*

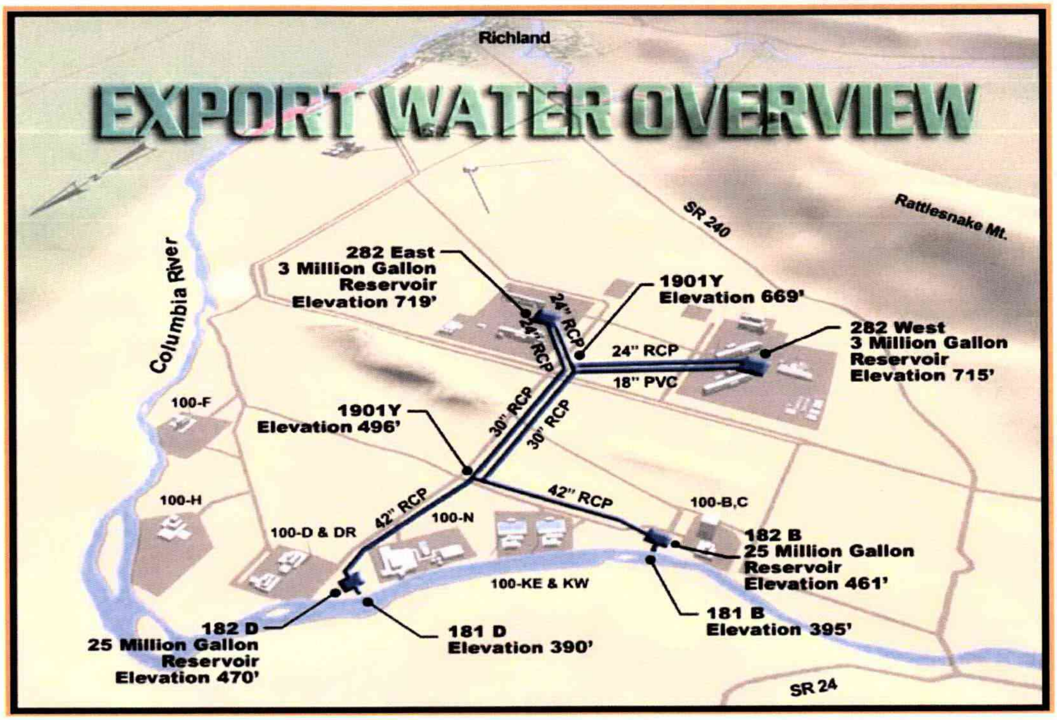
3.4.2 Anthropogenic Recharge

Anthropogenic recharge has historically had a much more dramatic effect on groundwater at the 100-B/C, 100-K, 100-D, and 100-H Areas.

3.4.2.1 100-B/C Area

One facility of particular interest regarding its potential contribution to groundwater contaminant distribution is the export water system (Figure 3-28). The export water system (including the 182-B reservoir) is an operating system that has affected contaminant transport and groundwater flow. Leaks from the export water system basin (182-B reservoir) are potentially affecting groundwater in the 100-B/C Area and provide a pathway for contaminants to reach the soil and groundwater.

Raw water is used in large quantities (millions of gallons per day) at the Hanford Site for process water, fire control, dust suppression, and other non-potable uses. Water is pumped from the Columbia River to large-capacity reservoirs located in the 100 Areas using the export water system. These reservoirs supply a network of large-diameter (101 cm [3.5-ft]) pipelines to smaller pipelines traversing the 100 Areas and connecting to moderately sized distribution reservoirs located on the Central Plateau. A key component of this system is the 182-B reservoir, which is one of two remaining structures on the Hanford Site that is used to store large quantities of untreated, raw water, and it is the primary reservoir. The other reservoir used for this purpose is located in the 100-D Area and is used as the backup facility (DOE/RL-2008-46-ADD3).



Source: DOE/RL-2008-46-ADD3, *Integrated 100 Area Remedial Investigation Study/Work Plan, Addendum 3: 100-BC-1, 100-BC-2, and 100-BC-5 Operable Units.*

Figure 3-28. Export Water System Plan View

Because the 182-B reservoir is one of the few facilities still operating at the Hanford Site from the Manhattan Project era, its age and condition are of concern. During its operation, the reservoir chronically leaked from cracks and construction joints, resulting in a persistent groundwater mound beneath. Although numerous buildings and waste sources have been removed or demolished since reactor deactivation, export water system components are located near facilities and waste sites that were demolished in place before current regulatory standards were applicable and, thus, possibly contain residual contamination

3.4.2.2 100-D and 100-H Areas

When the reactors were operational, substantial quantities of reactor coolant water were discharged to the ground via intentional and unintentional pathways. For the 100-H Area, approximately 2 trillion L (3.5 trillion gal) of reactor coolant passed through H Reactor between 1949 and 1965. For the 100-D Area, the D and DR Reactor cooling water retention basins and/or their attendant conveyance piping leaked chronically for decades, which resulted in a substantial groundwater mound forming beneath the area, centered beneath the retention basins and extending beneath the entire the 100-D Area. The mound exhibited a maximum observed height of about 3 m (10 ft) above the natural static water table.

From March through June 1967, a reactor coolant injection test was conducted in the 100-D Area (BNWL-CC-1352, *Ground Disposal of Reactor Coolant Effluent*). Three months prior to final cessation of D Reactor operations, the reactor coolant stream from the 100-D Area was routed directly to the ground at the 100-D emergency crib trench. Over 12.9 billion L (3.4 billion gal) of reactor coolant effluent were disposed to the trench during a 4-month period (BNWL-CC-1352), creating a groundwater mound up to 9.1 m (30 ft), which most likely increased the spread of contaminated groundwater through the highly permeable saturated Hanford formation sediment across the Horn.

Some locally enhanced recharge still occurs at the 100-D Area as a result of ongoing operations. The 182-D reservoir remains in use as one of two sources of untreated raw water (i.e., non-potable water) to supply the Hanford Site. Results of water-level monitoring at the 182-D reservoir indicate that approximately 31 million L (8.2 million gal) of water leaked to the ground between November 2005 and March 2006. Three distinct leakage events were identified and are summarized in SGW-38338:

- November 5 through December 15, 2005: Approximately 22 million L (5.8 million gal)
- January 1 through February 3, 2006: Approximately 4.9 million L (1.3 million gal)
- February 23 through March 13, 2006: Approximately 4.5 million L (1.1 million gal).

Leakage rates were 386 L/min, 100 L/min, and 163 L/min (102 gallons per minute [gpm], 26 gpm, and 43 gpm), respectively, for the three events. The water table below the reservoir rose temporarily in response to the first and third leakage events.

3.4.2.3 100-K Area

As shown in Table 3-8, over the lifetime of KE and KW Reactor operations, approximately 12 trillion L (about 3.5 trillion gal) of coolant were produced and passed through these reactors. After transport through the reactors, the effluent volume was discharged to the retention basins north of the reactors, and then either into the Columbia River through the outfalls or directly into the 116-K-1 Crib or the 116-K-2 Trench to the east of the reactors (Figure 2-4). The 116-K-1 Crib was used from February 1955 to May 1956 and received approximately 4E+7 L (about 1.1E+7 gal) of coolant containing 40 kg of sodium dichromate (about 14 kg of chromium) (PNL-6456, *Hazard Ranking System Evaluation of CERCLA Inactive Waste Sites at Hanford*).

Table 3-8. Estimate of Reactor Coolant Volume Passed Through the KW and KE Reactors

Reactor	Time Period	Flow-Through (gpm)	Flow-Through (L/yr)	Total Flow-Through (L)
KW Reactor	1955 to 1962	180,000	360 billion	2.9 trillion
	1963	200,000	400 billion	400 billion
	1964 to 1970	200,000	400 billion	2.4 trillion
KE Reactor	1955 to 1962	180,000	360 billion	2.9 trillion
	1963	200,000	400 billion	400 billion
	1964 to 1971	200,000	400 billion	2.8 trillion
			Total	**12 trillion**

Source: DOE/RL-2008-46, *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan.*

gpm = gallons per minute

The KW/KE retention basins were the sources that provided the largest volumes of coolant to the environment. The 116-KE-4 and 116-KW-3 retention basins received cooling water effluent (no recorded volume but estimated to be equivalent to the 681,374 to 757,082 L/min [180,000- to 200,000-gpm] rates used to cool each of the reactors) from the KE and KW Reactors, respectively, for radioactive decay and thermal cooling prior to release to the Columbia River. The retention basin tanks and associated effluent pipelines developed leaks during their operating lifetimes. For example, varying amounts of losses from the 116-KE-4 site were observed. The leakage rate from the basin itself was estimated to be 37,854 to 75,708 L/min (10,000 to 20,000 gpm); the leakage rate from butterfly valves that allowed flow to the 116-K-2 Trench was estimated to be 18,927 to 37,854 L/min (5,000 to 10,000 gpm) (WHC-SD-WM-TI-239, *100-K Area Technical Baseline Report*).

The 116-K-2 Trench was used through the reactor operational period from 1955 until 1971. Other than the 18,927 to 37,854 L/min (5,000- to 10,000-gpm) flow through the butterfly valve, the 116-K-2 Trench also received unknown quantities of contaminated effluent from floor drains in the KE and KW Reactors (low volume). Additional sources included approximately 1,893 L/min (500 gpm) (995,000,000 L/year, or 17 billion L over 17 years) of KE and KW Reactors metal storage basin overflow, as well as occasional tanks of process cooling water that was collected after a fuel-cladding failure (DOE/RL-2008-46). As evidenced by water levels in wells, a large fraction of trench discharges moved upgradient during the 16 years of use. Water levels in well 699-78-62, located approximately 1.6 km (1 mi) upgradient of the 116-K-2 Trench, increased more than 3.4 m (11 ft). Water levels in wells located southwest and west of the trench (i.e., 699-73-72 and 699-70-68) increased more than 1.5 m (5 ft) during reactor operations.

Other sources of chromium discharges were leaks or overflows in and around the outfall structure, releases from small liquid discharge facilities, piping that carried reactor coolant, and some solid wastes (e.g., sludge). Of these sources, losses around the outfall structure may have been substantial, as more than 90 percent of the reactor coolant apparently discharged through the facility. Other facilities received much smaller volumes of liquids (and solids) compared to the retention basins and the 116-K-2 Trench and could have contributed relatively minor amounts of chromium to the subsurface.

3.5 Processes

The groundwater flow system beneath the Hanford Site represents a primary environmental pathway for contaminant movement away from source areas. This pathway ultimately discharges into the Columbia River. River flow and water surface elevation are primarily governed by releases at Priest Rapids Dam and by pool elevation at McNary Dam. Water release at Priest Rapids Dam is heavily influenced by power generation needs and, thus, has a strong diurnal cycling during much of the year, in addition to seasonal peaks caused by higher inflows to the dam during spring and early winter. The magnitude of these diurnal river-stage fluctuations can, on occasion, exceed the seasonal fluctuation of monthly average river stages. As discussed below, groundwater levels are significantly correlated with river stage, albeit with a lag in time and decreased amplitude of fluctuations. Water levels in wells more than 1 km (0.6 mi) away from the river can often have multiple damped peaks each associated with the occurrence of a significant river-stage peak followed by a significant drop.

The large magnitude of the river-stage fluctuations and the occurrence of inter-annual high river-stage events can also result in a significant component of flow through unsaturated porous media. Furthermore, the relatively high frequency of river-stage fluctuation results in riverbank storage during high stage followed by seepage out of the freshly exposed bank faces during low stage. Vadose zone flow and transport processes also potentially affect the leaching and migration of chromium from contaminated sediments above the water table.

3.5.1 River/Aquifer Interaction

Near the Columbia River, the groundwater flow system is influenced by the river flow system in a mixing zone of groundwater/river interaction. The principal features and terminology associated with the zone of interaction are illustrated in Figure 3-29.

Physical, chemical, and biological processes occur within the zone of interaction that can potentially alter the characteristics of the approaching groundwater (PNNL-13674, *Zone of Interaction Between Hanford Site Groundwater and Adjacent Columbia River: Progress Report for the Groundwater/River Interface Task, Science and Technology Groundwater/Vadose Zone Integration Project*). Information to date suggests that physical processes are the dominant influence on contaminant concentrations and fluxes at locations of discharge into the free-flowing stream of the Columbia River. Physical processes include (1) layering and mixing of groundwater and river water, which infiltrates the banks and riverbed sediments; and (2) varying hydraulic gradients caused by river stage fluctuations. The hydraulic gradient is greatly increased near the river during periods of low flow. As the river stage increases, the gradient becomes less and may even reverse direction in response to the highest stages that occur. Chemical processes may change the characteristics of a contaminant in groundwater so it becomes less mobile (e.g., adsorbs to sediment or precipitates). Biological activity in the zone may capture contaminants and immobilize them or it may introduce the contaminants to the food chain.

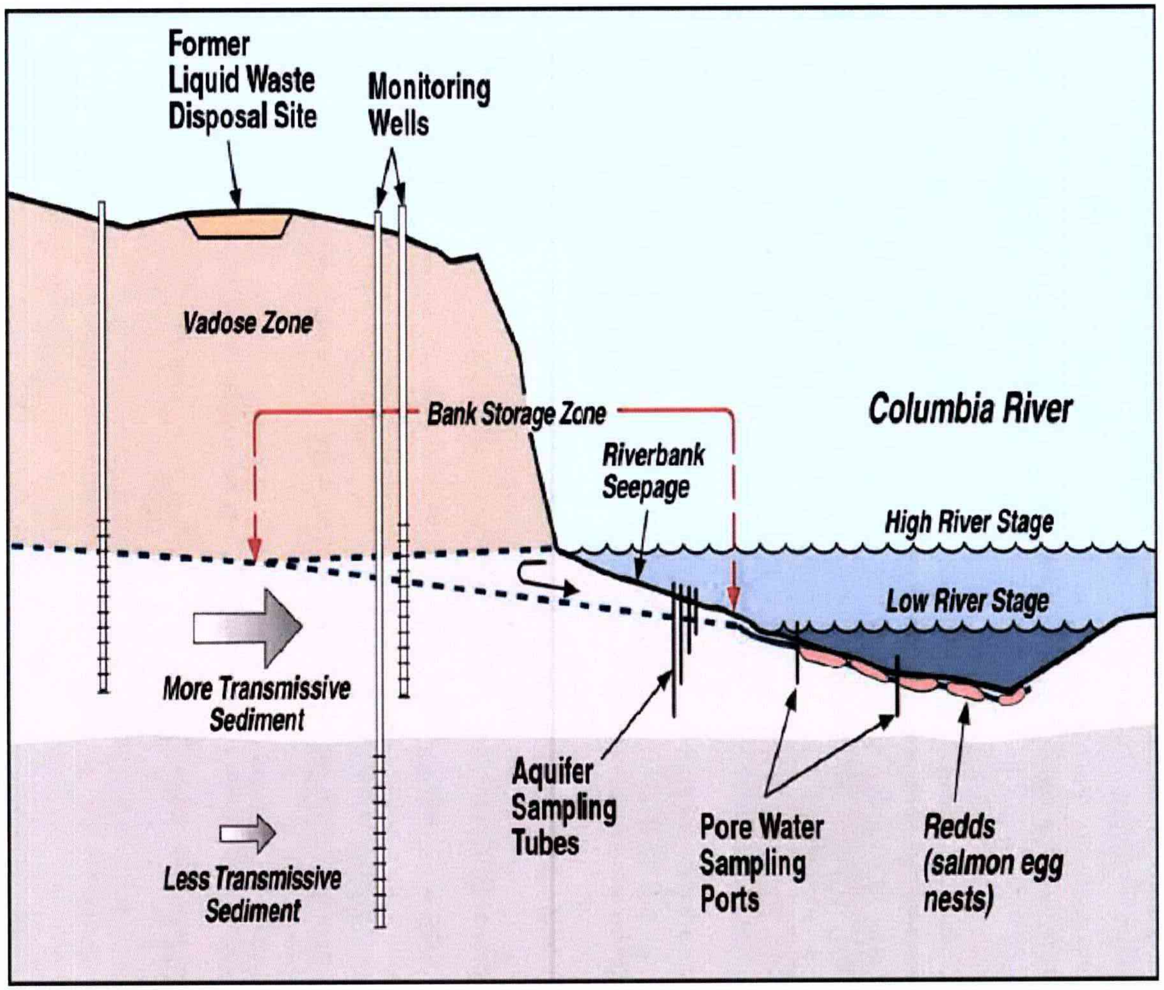
Discharge into the river environment occurs across two primary interfaces. The first is the region between the high and low river stages, generally referred to as the riparian zone (Figure 3-29). Within this region, discharge from the zone of interaction appears as riverbank seepage during periods of low river stage. River water infiltrates the banks during periods of high river stage and forms either a layered system or a mixture during interaction with the approaching groundwater. As seepage continues to flow during the period of low river stage, the composition of the seepage may change dramatically from nearly pure river water to primarily groundwater (PNNL-13674).

A second interface exists within the river channel substrate that is constantly submerged (i.e., at elevations below the lowest river stage) (Figure 3-29). This region contains sediment porewater that is influenced by the entrainment of Columbia River water and the gradual influx of groundwater upwelling from the underlying aquifer (PNNL-13674). The riverbed provides the spawning habitat for fall Chinook salmon.

3.5.2 Impact of Seasonal Fluctuations and Pump-and-Treat on Groundwater Conditions

As previously discussed, groundwater flow in the 100 Areas fluctuates in response to the river stage in the Columbia River, which is 2 to 3 m (6.6 to 9.8 ft) higher during high water level in the late spring and early summer versus the fall. As a result, the dynamics of groundwater flow near the river change seasonally. The aquifer response is most pronounced near the shoreline but extends inland of the shore.

Figure 3-30 illustrates the river/aquifer interaction in the 100-D Area (DOE/RL-2009-15, *Calendar Year 2008 Annual Summary Report for the 100-HR-3, 100-KR-4, and 100-NR-2 Pump-and-Treat Operations*). A comparison of fall and spring groundwater levels (Figure 3-30) suggests that the rise in the river stage due to the spring runoff causes changes in groundwater levels up to several hundreds of meters inland in the aquifer that attenuate further inland; most of the large-scale changes are within several tens of meters of the Columbia River.



Source: PNNL-13674, *Zone of Interaction Between Hanford Site Groundwater and Adjacent Columbia River.*

Figure 3-29. Schematic of Principal Features and Monitoring Within the River/Aquifer/Vadose Zone

During low river stage in the fall and winter, the flow is toward the river, whereas during high river stage in the spring and summer, the flow is locally from the river inland. These observations suggest that the Columbia River is primarily a gaining reach during times of low flow and may become primarily a losing reach during times of high flow. This interpretation is supported by concentration contours presented in Figure 3-20. This indicates that during spring runoff when the river stage is high, chromium concentrations are less than 22 μg/L along the entire shoreline, whereas during late fall when the river stage is low, chromium concentrations are greater than 22 μg/L at several locations along the shoreline.

Similar river/aquifer interaction effects are also evident in the 100-H Area (Figure 3-31). As shown in Figure 3-31, the river stage is 2 to 3 m (6.6 to 9.8 ft) higher during high water level in the late spring and early summer versus the fall.

Relative to pump-and-treat impact, groundwater flow in the 100-H Area, for example, occurs in sands and gravels of variable conductivity and is influenced by the injection and extraction well networks for the pump-and-treat system, as well as seasonal fluctuations in the Columbia River. Regional groundwater flow near the 100-H Area is toward the Columbia River. The aquifer near the 100-H Area is located in the sands and gravels of the Hanford formation.

Locally, groundwater flow in the 100-H Area is generally radially outward from the injection wells toward a series of extraction wells. Flow is generally toward the river between the injection well field and the Columbia River, parallel to the river for less than 200 m (656 ft) both upriver and downriver of the injection wells, and then perpendicular to the river further away from the injection wells (Figure 3-30) (DOE/RL-2009-15).

3.6 Nature and Extent of Contamination

3.6.1 100-HR-3 Operable Unit Contamination Sources

The known and potential sources of observed groundwater contamination are numerous; however, an evaluation of the sources indicates that a limited number are likely candidates for current groundwater contamination at both the 100-D and 100-H Areas. This section focuses on the 100-D Area due to the presence of more extensive contamination in this area.

The 100-D Area's reactor cooling water contributed large volumes of contaminated water containing approximately 2 mg/L of chromium. For many years during reactor operations, groundwater beneath the 100-D Area consisted largely of reactor coolant and would have exhibited widespread and uniform contamination at about 2 mg/L of chromium. After reactor operations ceased in 1967, the reactor coolant contribution ceased and the coolant in contaminated groundwater dispersed.

The current groundwater contamination plumes exhibit chromium concentrations greater than the historic coolant concentration, suggesting that current conditions result from releases of higher concentration source material. The higher concentration source material included the sodium-dichromate salt and high- and moderate-concentration sodium-dichromate solutions used as feed and working solutions, respectively. These higher concentration materials were used at only four locations and the conveyance lines that connected them. The candidate source areas are described in SGW-38338; the source areas are listed below and are shown in Figure 3-32:

- 108-D Building and its associated waste disposal cribs (storage and handling of sodium-dichromate salt and high- and moderate-concentration solutions; and disposal to ground of chromium-bearing decontamination solutions)

- 185-D and 190-D Buildings and the solution storage tank location adjacent to former 190-D Building (storage and handling of high- and moderate-concentration solutions)
- Former railcar unloading station (handling of high-concentration solutions)
- 183-DR Building (handling of moderate-concentration solutions).

Potential contribution to vadose zone contamination and subsequent groundwater contamination may also be related to leaks from the 100-D Area process sewer line, which is suspected to have received sodium-dichromate solutions in various concentrations.

3.6.2 100-KR-4 Operable Unit Contamination Sources

Sodium dichromate (the chromium source) was primarily delivered in concentrated liquid form and was used in aqueous solutions of varying concentrations. The principal use for sodium dichromate was to control corrosion in reactor process tubing. High-concentration acidic sodium-dichromate solutions (greater than 70 weight percent) were used as stock material from 1955 until closure of the KE and KW Reactors in 1970 and 1971 (Figure 2-4). These materials were received by railcar and tanker trucks and then stored in tanks 120-KW-5 and 120-KE-6. Based on 0.5 to 2 parts per million (ppm) sodium-dichromate dilution in cooling water, the chromium concentrations were about 168 to 680 parts per billion (ppb). Records indicate that 100-K Area water treatment processes mixed sodium dichromate with cooling water concentrations to between 1.8 to 2 ppm dichromate concentration initially, with diminishing concentrations implemented at each plant over time (down to 1.0 ppm at the KW Reactor in 1964 and 0.5 ppm at the KE Reactor in 1968 (DUN-4847, *Quarterly Report Contamination Control – Columbia River April - June 1968*). Sodium dichromate use ranged from approximately 20,000 kg/month initially for each reactor, to between 5,000 and 10,000 kg/month near the end of production operations. Figure 3-33 shows the locations of the 100-KR-4 OU chromium waste sites.

3.6.3 100-BC-5 Operable Unit Contamination Sources

Sources of contamination at the 100-BC-5 OU include spills, leaks, and past liquid and solid waste disposal sites. Contamination is found within the vadose zone and groundwater and has migrated to the Columbia River. The primary sources of contamination in the 100-B/C Area are two water-cooled nuclear reactors (B and C Reactors) and the structures (e.g., fuel storage basins) and processes (e.g., sodium-dichromate process) associated with reactor operations. The reactors were built to irradiate uranium-enriched fuel rods from which plutonium and other special nuclear materials could be extracted, with the extraction process conducted in the 200 Areas.

The reactors and processes associated with operations generated large quantities of liquid and solid wastes. Effluent generated during operations consisted primarily of contaminated reactor cooling water, fuel storage basin water, and decontamination solutions. Cooling water consisted of Columbia River water treated to remove dissolved solids and enhanced with chemicals to reduce corrosion. Cooling water contaminants consisted of fuel materials, fission and irradiation byproducts, and hexavalent chromium (used as a corrosion inhibitor). Hexavalent chromium, strontium-90, and tritium are recognized as the primary contaminants; chromium is the primary COC in the groundwater. Solid wastes consisted of sludge, reactor components, and various other contaminated items. Waste generated from reactor operations was contaminated with radionuclides, hazardous chemicals, or both.

The primary release mechanisms in the 100-B/C Area are intentional and unintentional releases. Liquid contaminants were released to the environment by discharging effluent to temporary surface impoundments, cribs, ditches, and the Columbia River. Solid waste was placed in burial grounds. Figure 3-34 shows the location of 100-B/C Area chromium waste sites.

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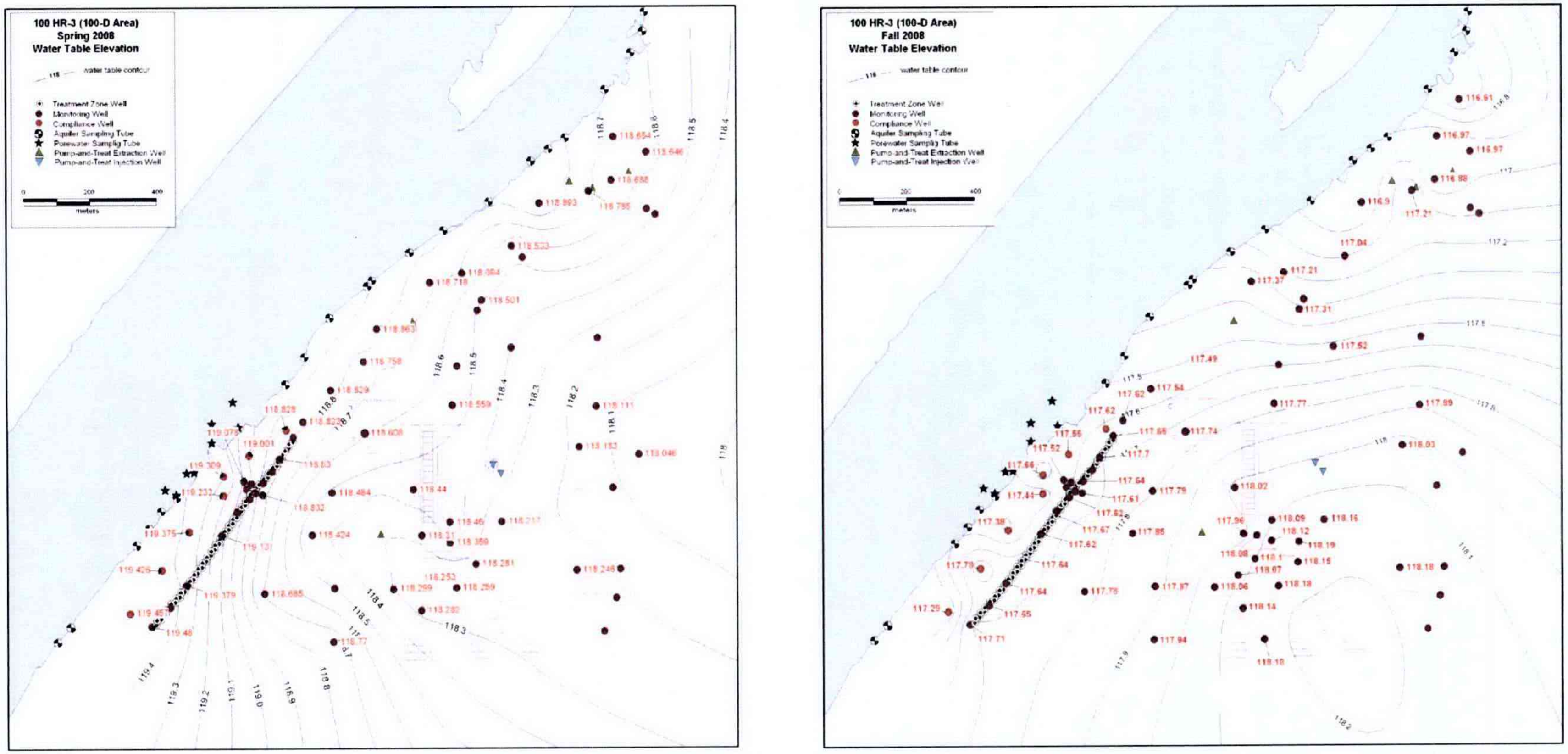
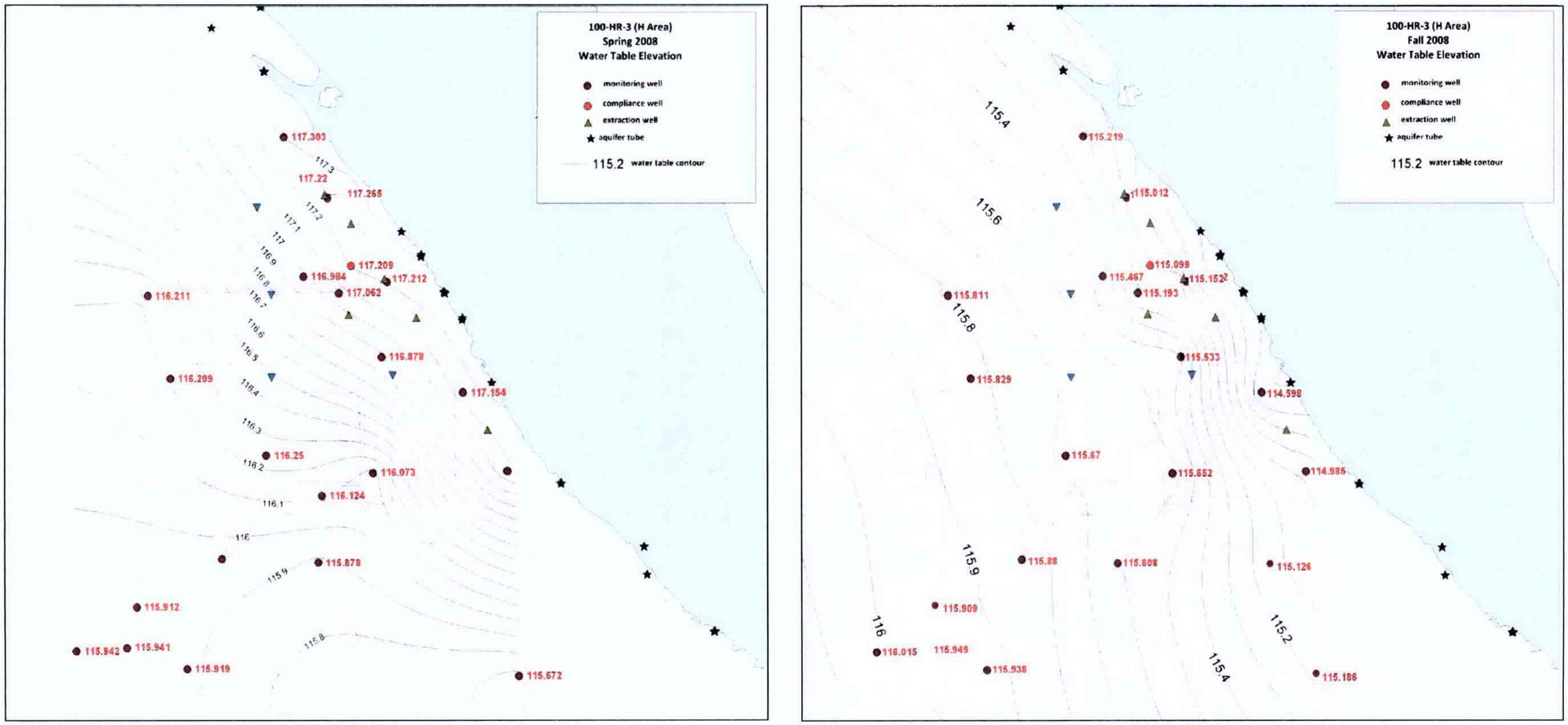


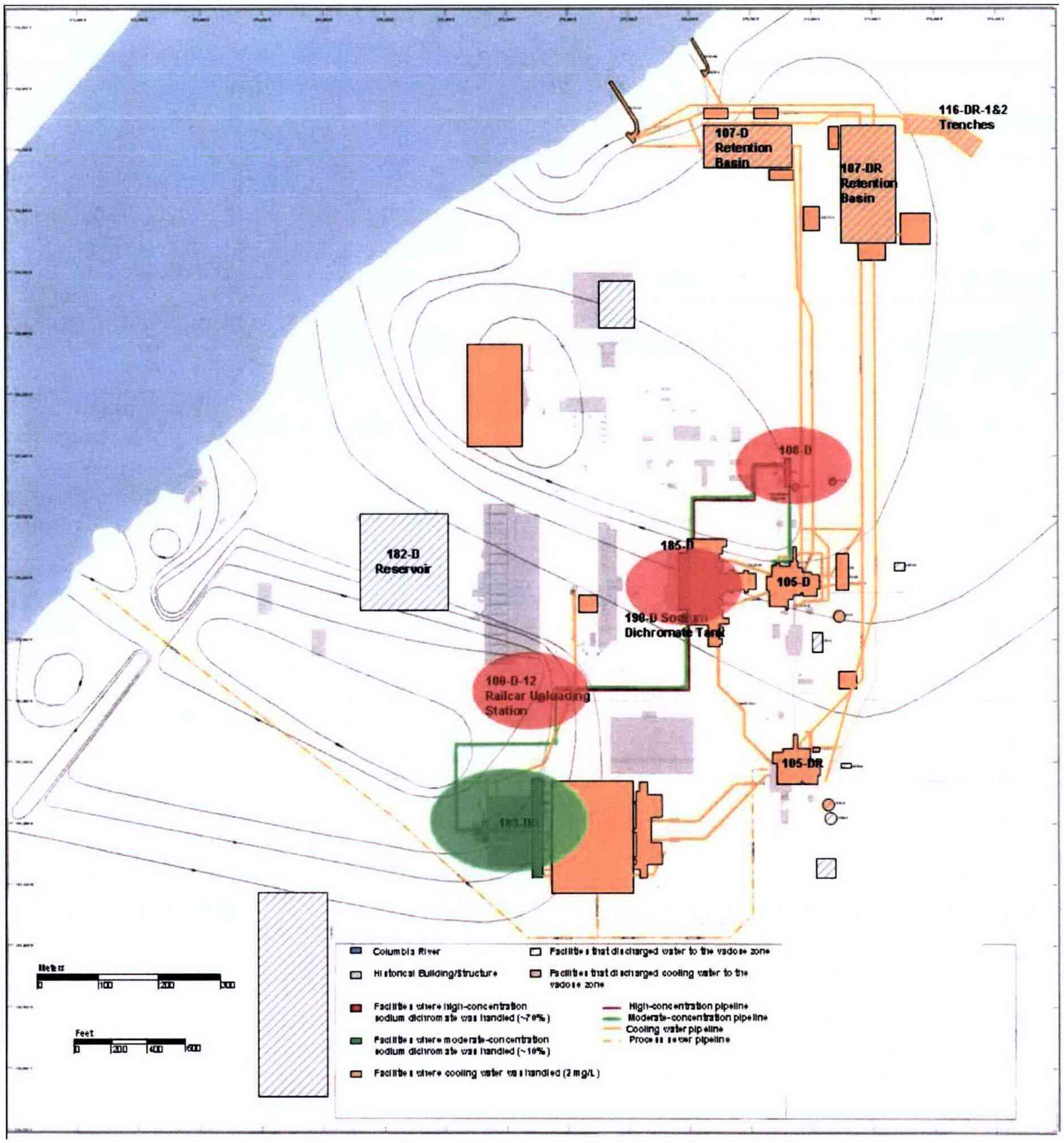
Source: DOE/RL-2009-15, *Calendar Year 2008 Annual Summary Report for the 100-HR-3, 100-KR-4, and 100-NR-2 Pump-and-Treat Operations.*

Figure 3-30. 100-D Area June and November 2008 Measured Water Table Comparison



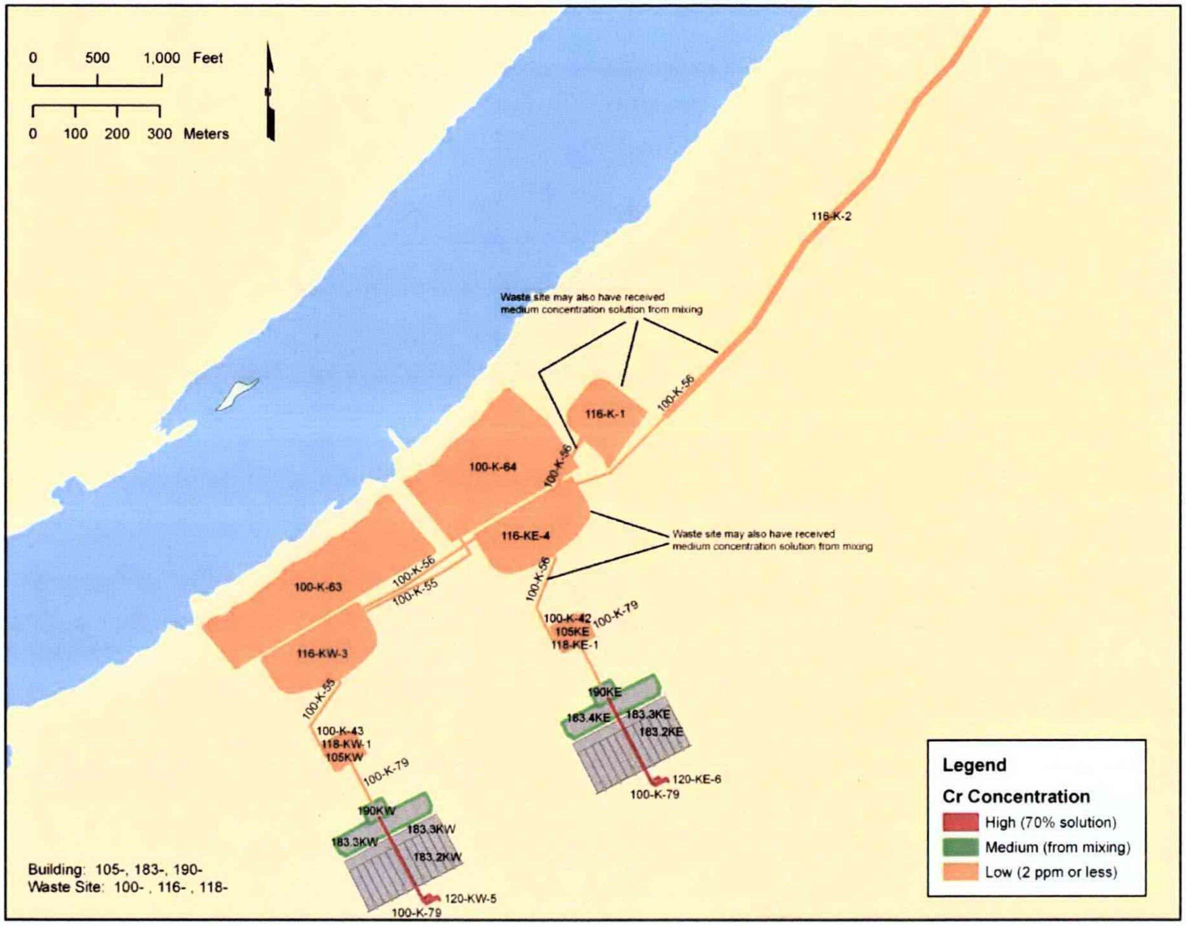
Source: DOE/RL-2009-15, *Calendar Year 2008 Annual Summary Report for the 100-HR-3, 100-KR-4, and 100-NR-2 Pump-and-Treat Operations.*

Figure 3-31. 100-H Area May and November 2008 Measured Water Table Comparison



Source: SGW-38338, *Remedial Process Optimization for the 100-D Area Technical Memorandum Document.*

Figure 3-32. 100-D Area Probable Vadose Zone Source Areas Contributing to Current Hexavalent Chromium Groundwater Plumes



Source: DOE/RL-2008-46, *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan.*

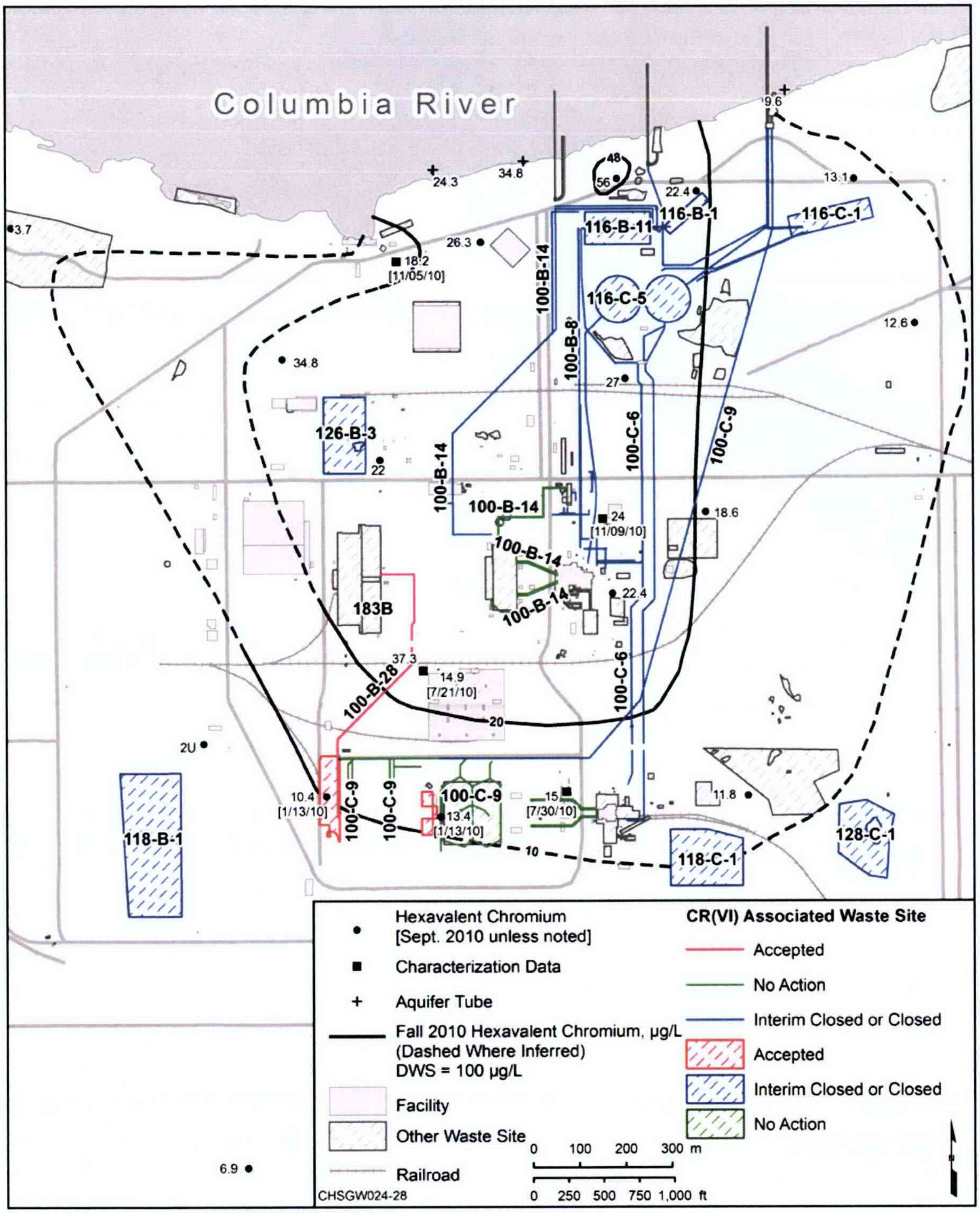
Figure 3-33. Chromium Process and Waste Sites Identified as Receiving a Chromium Waste Stream

3.6.4 Historical Plume Maps for Hexavalent Chromium

Figures 3-35, 3-36, and 3-37 show the historical shape and extent of hexavalent chromium plumes in the 100-H, 100-D, and 100-K Areas, respectively.

3.6.4.1 100-D Area

Figure 3-35 presents maps depicting hexavalent chromium plumes in the 100-D Area for the period from 1995 through 2007. The shape and extent of the 100-D Area hexavalent chromium plume varied significantly from 1995 to 1999 as additional wells and aquifer tubes were added to the monitoring network. Since 2003, the general plume configuration has remained nearly the same. The major plumes are in the area of the In Situ Redox Manipulation (ISRM) barrier, extending upgradient to well 199-D2-8; other plumes are located in the reactor areas. The plumes likely remained separated due to injection into wells 199-D5-42 and 199-D5-106, previous leakage from the 182-D reservoir, and other water discharges. In 2007, the 182-D reservoir operation logs indicated that the reservoir was no longer leaking, and well 199-D5-106 was no longer used as an injection well after the fall of 2007.



Source: DOE/RL-2008-46-ADD3, *Integrated 100 Area Remedial Investigation Study/Work Plan, Addendum 3: 100-BC-1, 100-BC-2, and 100-BC-5 Operable Units.*

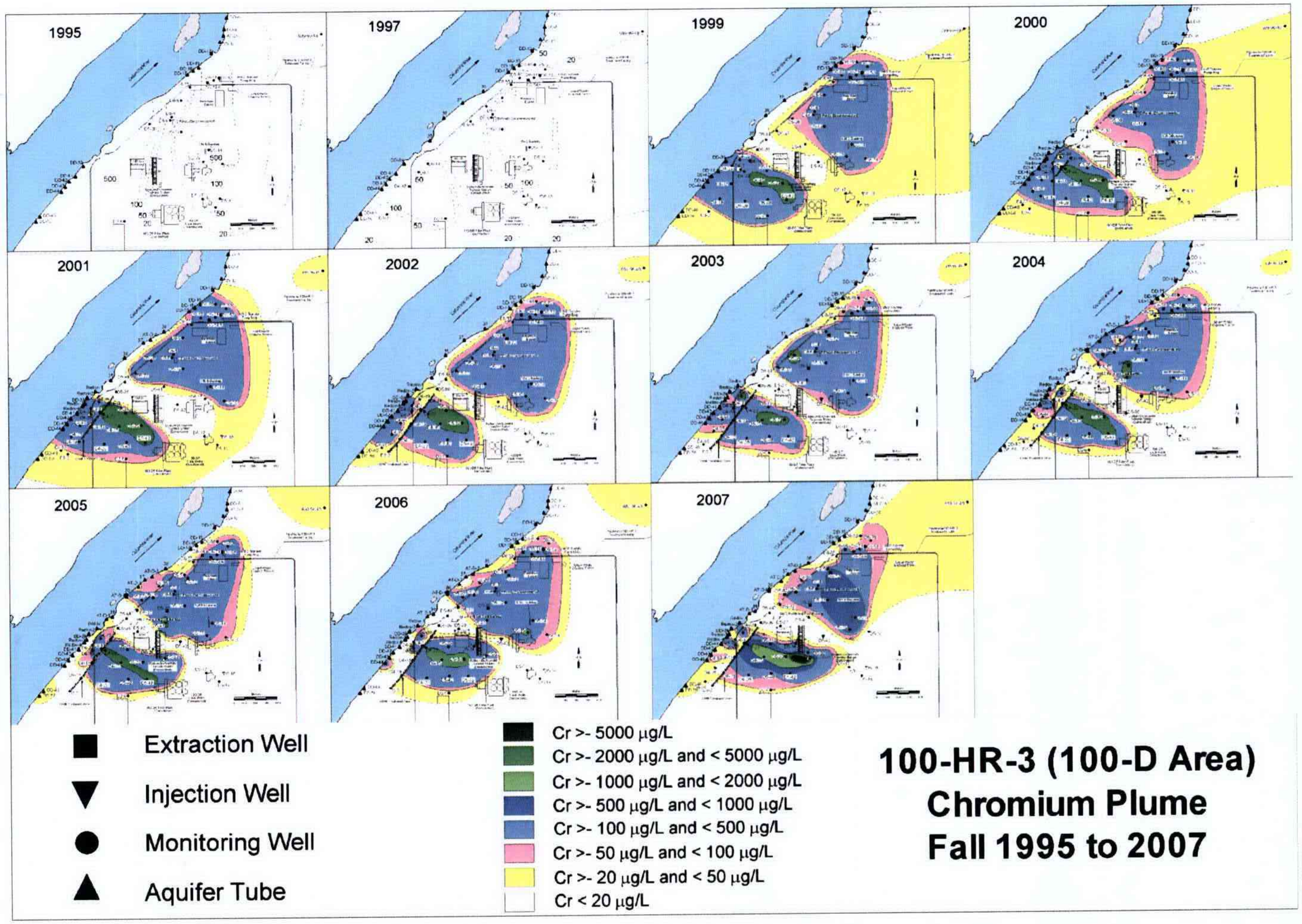
Figure 3-34. 100-B/C Area Hexavalent Chromium Waste Sites

Uncertainty regarding future groundwater impact for the 100-D Area includes the following issues (DOE/RL-2009-15):

- Uncertainty in effectiveness of interim remedial actions: The interim remedial actions implemented, for example, at the 100-D Area (i.e., the ISRM at the southern plume, and the 100-D Area pump-and-treat system to the north) are both intended to intercept downgradient portions of groundwater plumes. As a result, these interim actions are neither capable of, nor intended to, address secondary sources in the vadose zone or in groundwater. These systems, therefore, will require operation over prolonged periods to ensure interception of the plumes as the plumes continue to develop and migrate toward the Columbia River. Of continuing concern is the longevity of the ISRM barrier, which exhibits limited effectiveness and duration in the highest concentration portion of the southern plume. In light of the recent discovery of very high groundwater chromium concentrations upgradient of the ISRM zone, the long-term efficacy of this action seems doubtful.
- Uncertainty in management of secondary sources: The persistence of groundwater contamination at the 100-D Area, for example, by chromium indicates the presence of substantial secondary sources in the vadose and groundwater in the affected areas. The groundwater contamination cannot be successfully controlled until these sources are managed in a manner that prevents, or minimizes, future contribution to the groundwater plume(s). The recent observation of extremely high chromium in groundwater in boreholes near the former railcar unloading station indicates the magnitude of a secondary source in that area. Relatively few borings and monitoring wells in the upgradient portion of the northern plume lobe in the 100-D Area provide limited information to identify and characterize the apparent secondary source(s) in that area. The persistence of a lower concentration plume in that area suggests the potential presence of more diffuse secondary sources in the vadose zone of the northern plume lobe relative to that inferred to be present in the southern lobe.

3.6.4.2 100-H Area

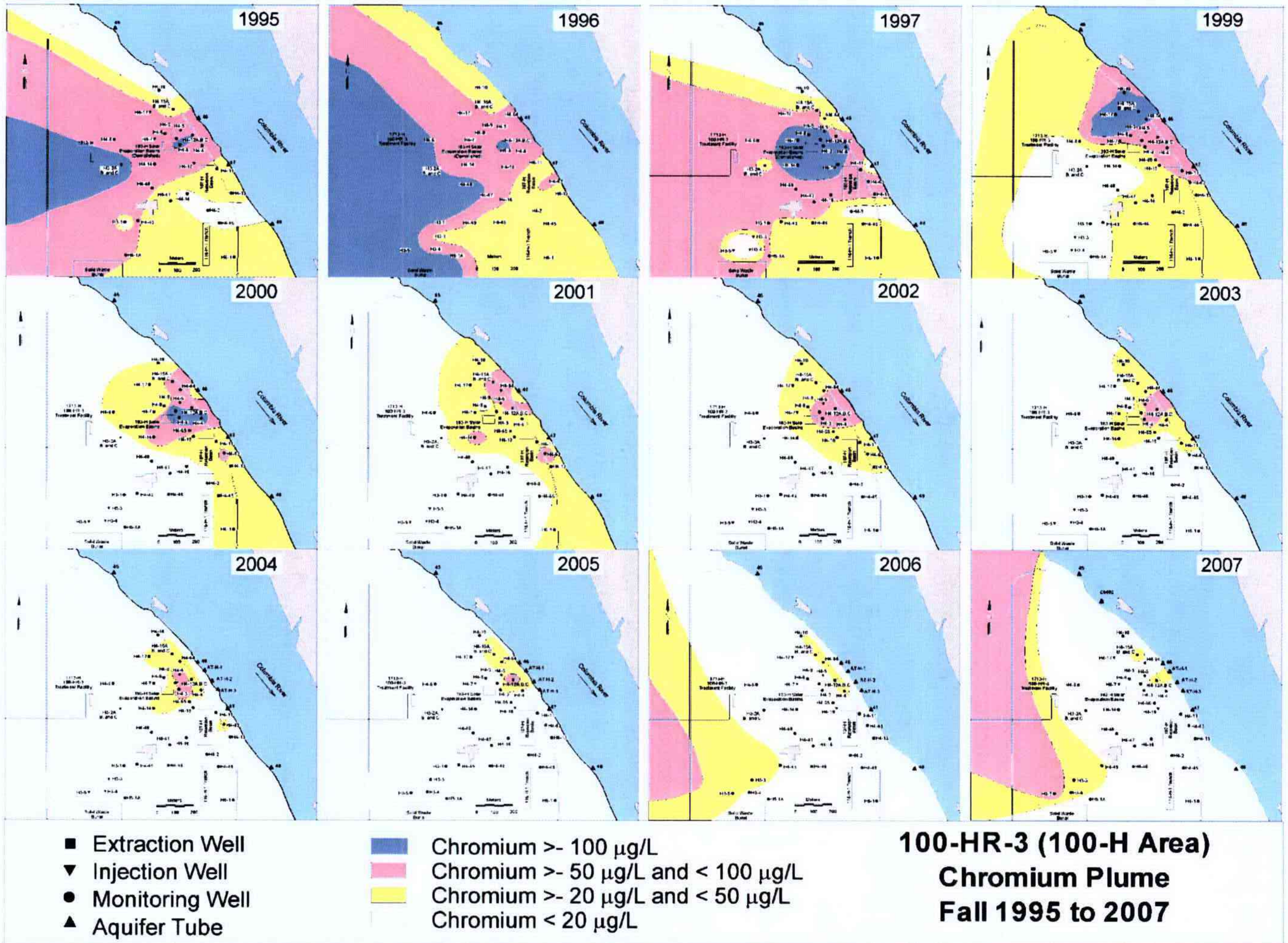
Figure 3-36 presents maps depicting hexavalent chromium plumes in the 100-H Area for the period from 1995 through 2007. The hexavalent chromium plume changed dramatically since pump-and-treat operations began in 1997. The areal extent of the plume in 2007 consisted of a narrow strip along the 100-H Area shoreline, downgradient of H Reactor and the former liquid effluent disposal facilities. Hexavalent chromium concentrations in the plume were in the range of 20 to 50 μg/L. The hexavalent chromium plume in the Horn was moving into the 100-H Area.



Source: DOE/RL-2009-15, *Calendar Year 2008 Annual Summary Report for the 100-HR-3, 100-KR-4, and 100-NR-2 Pump-and-Treat Operations*.

Note: Changes in the 20 µg/L contour represent variation in interpretations and data point density at the time of map preparation.

Figure 3-35. 100-D Area Chromium Plumes, 1995 to 2007



Source: DOE/RL-2009-15, *Calendar Year 2008 Annual Summary Report for the 100-HR-3, 100-KR-4, and 100-NR-2 Pump-and-Treat Operations.*

Figure 3-36. 100-H Area Chromium Plume, 1995 to 2007

3.6.4.3 100-K Area

Figure 3-27 presents maps depicting hexavalent chromium plumes in the 100-K Area for the period from 1997 through 2007. The fall 2007 hexavalent chromium groundwater plume in the 100-K Area is depicted as three separate plumes based on the likely principal source:

- The largest plume is likely a result of reactor coolant discharges to the 116-K-2 Trench from 1955 through 1971, which created a groundwater mound and raised the water table up to 3 m (10 ft) at inland well 699-78-62. This plume is being remediated by the 100-KR-4 pump-and-treat system.
- A second hexavalent chromium plume is located near the KW Reactor. The high hexavalent chromium concentration in well 199-K-137, located upgradient of the KW Reactor, suggests that the plume may have been caused by a leak or spill of concentrated sodium-dichromate solution. This plume is being remediated by the KW pump-and-treat system.
- The third hexavalent chromium plume is in the area of the KE Reactor and appears to extend east into the upgradient end of the 116-K-2 Trench area and plume. The source of this plume is likely a combination of leakage from water treatment facilities serving the KE Reactor and also infiltrated reactor effluent from the 116-K-2 Trench.

3.6.4.4 100-N Area

Hexavalent chromium is present in two areas within the 100-N Area. One of the areas where hexavalent chromium is present is the western portion of the 100-N Area, in a plume that has migrated northeastward from the 100-K Area (Figure 3-38). This plume will be addressed by 100-K Area remedial actions.

In the 100-N Area, hexavalent chromium has been sampled from 11 monitoring wells and 12 aquifer tubes, with a total of 23 analyses from wells and 22 analyses from aquifer tubes. The samples (all non-filtered) revealed hexavalent chromium concentrations up to 330 μg/L in well 199-N-3 in 1969 and 24 μg/L in aquifer tube C6318 in 2008. The last hexavalent chromium detection above 20 μg/L (concentration protective of aquatic receptors) detected in a monitoring well was a concentration of 60.3 μg/L from well 199-N-64 in 2005, which was the only hexavalent chromium sample collected from this well.

Total chromium samples have been collected since 1985 from wells in the 100-N Area. Exceedances of the state and federal DWSs were detected in several wells sampled in the early and mid-1990s (e.g., well 199-N-17); these wells have not been sampled since that time. In one well completed beneath the RUM (well 199-N-80), which was completed in a 1.5 m (5-ft) sand layer, concentrations of total chromium have exceeded the federal DWS since 1992, with concentrations ranging from 130 to 234 μg/L.

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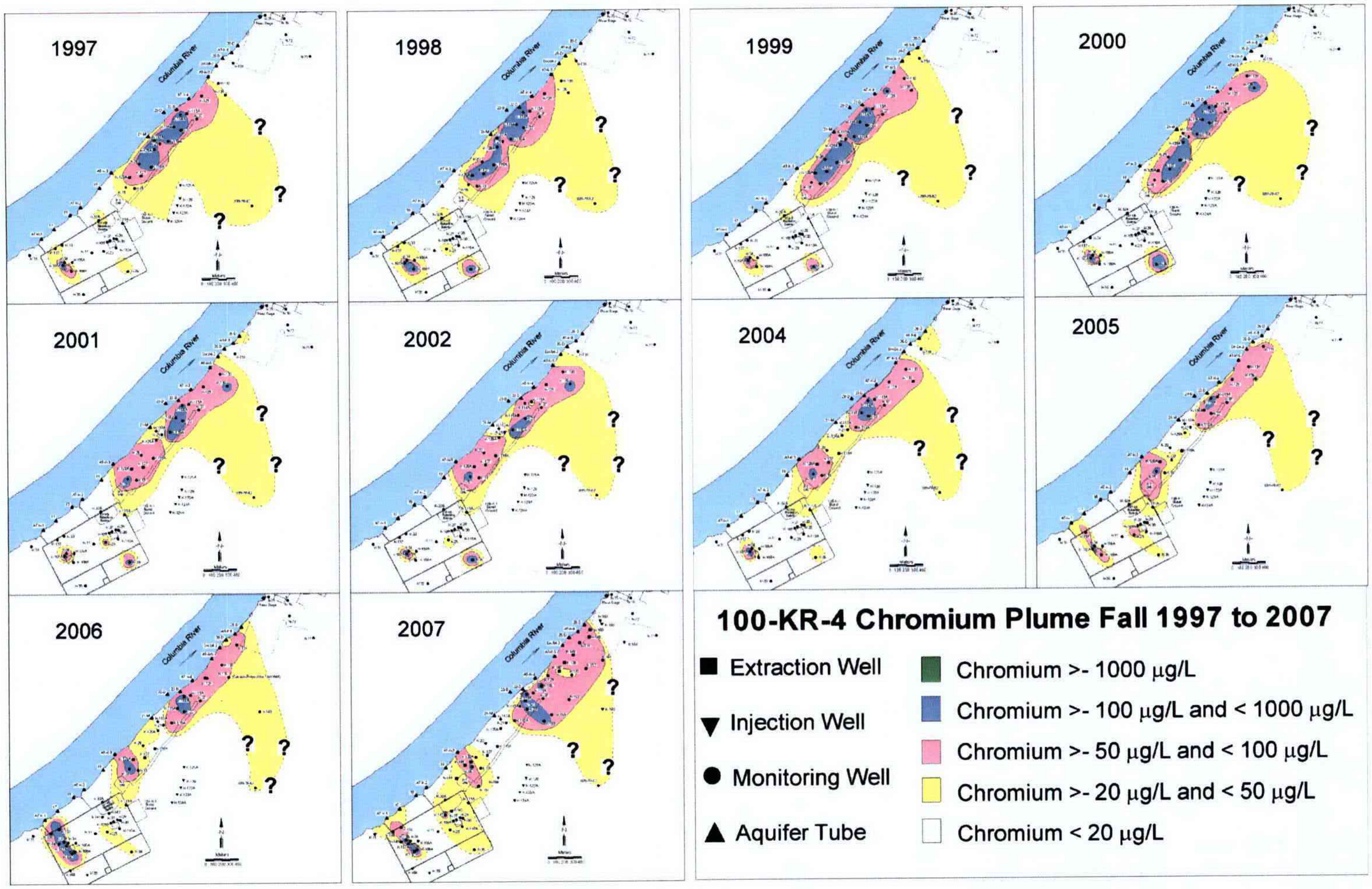

Source: DOE/RL-2009-15, *Calendar Year 2008 Annual Summary Report for the 100-HR-3, 100-KR-4, and 100-NR-2 Pump-and-Treat Operations.*

Figure 3-37. 100-KR-4 Chromium Plumes, 1997 to 2007

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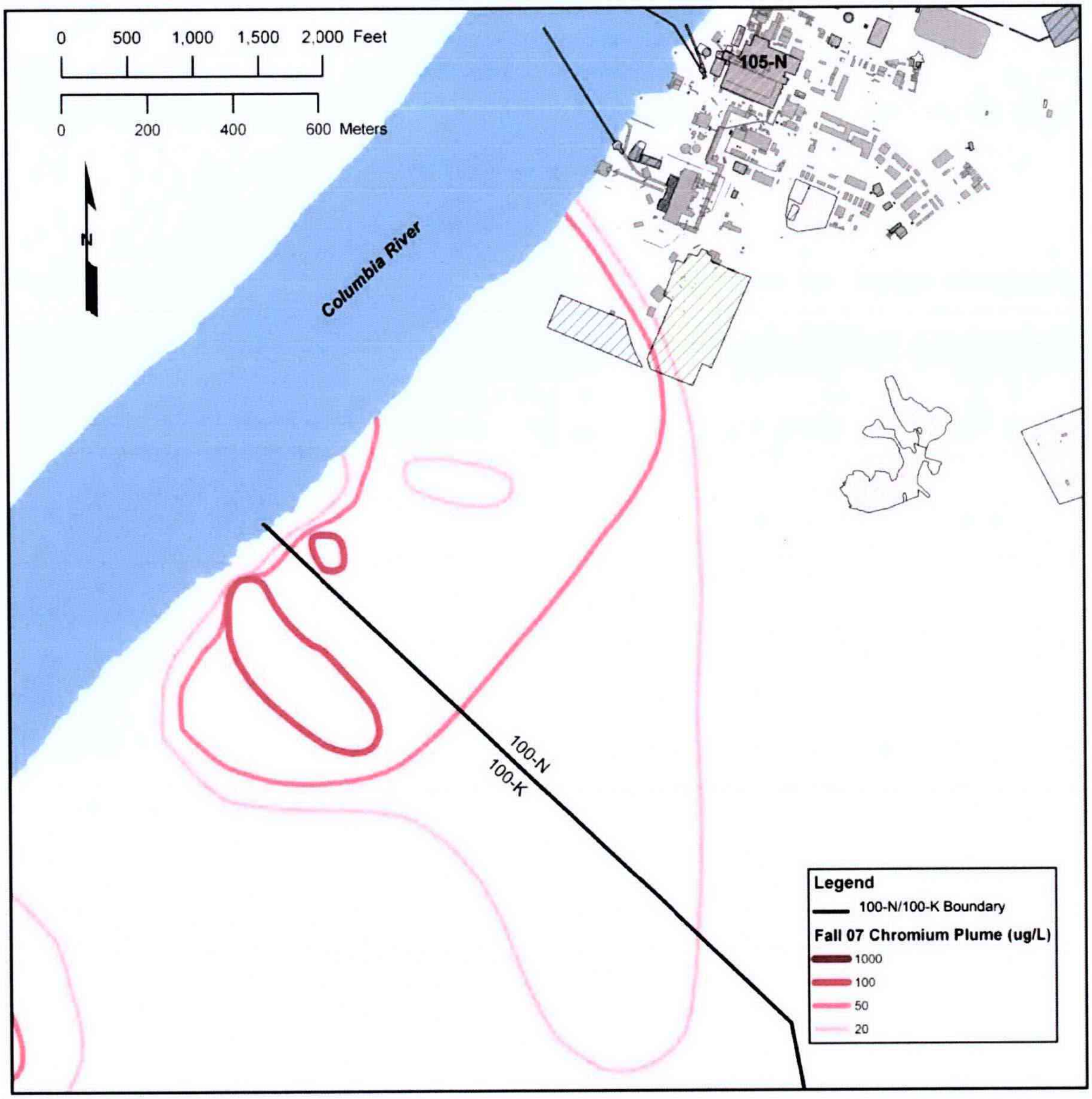

Source: DOE/RL-2008-46-ADD5, *Integrated 100 Area Remedial Investigation Study/Work Plan, Addendum 5: 100-NR-1 and 100-NR-2 Operable Units.*

Figure 3-38. Hexavalent Chromium on the Western Portion of the 100-N Area Unconfined Aquifer

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4 Flow and Transport Properties

A number of parameters are needed to model water flow and the transport of chromium. For the unconfined aquifer, saturated hydraulic conductivity and storage parameters are important inputs to the groundwater model. Data on bulk density, contaminant distribution coefficients (Kds), and longitudinal and lateral macrodispersivities are needed for modeling contaminant transport. Information on soil hydraulic properties (i.e., moisture content versus matric potential, and unsaturated hydraulic conductivity versus matric potential or moisture content relationships) is key to quantifying the moisture storage and flow properties of vadose zone sediments. This section provides a summary of existing data for the 100 Area vadose zone and unconfined aquifer flow and transport properties.

4.1 Vadose Zone Properties

A closed-form functional relation is typically used to describe the laboratory-measured soil moisture characteristics in numerical models. At the Hanford Site, van Genuchten-Mualem relationships ("A Closed-Form Solution for Predicting the Conductivity of Unsaturated Soils" [van Genuchten 1980]; "A New Model for Predicting the Hydraulic Conductivity of Unsaturated Porous Media" [Mualem 1976]) continue to be the most popular model to represent the characteristic curves. The van Genuchten (1980) moisture retention model is presented in the following (Equation 4-1):

$$\theta(h) = \theta_r + (\theta_s - \theta_r)\left\{1 + [\alpha h]^n\right\}^{-m}$$ **(Equation 4-1)**

where:

θ	=	volumetric moisture content (dimensionless)
h	=	matric potential or pressure head, which, for notational convenience, is considered as being positive (i.e., tension [cm])
θ_r	=	residual moisture content (dimensionless)
θ_s	=	saturated moisture content (dimensionless)
α	=	a fitting parameter (cm^{-1})
n	=	a fitting parameter (dimensionless)
m	=	$1 - 1/n$.

Combining the van Genuchten model with Mualem's (1976) model for unsaturated conductivity (Equation 4-2):

$$K(h) = \frac{K_s\left\{1 - (\alpha h)^{mn}\left[1 + (\alpha h)^n\right]^{-m}\right\}^2}{\left[1 + (\alpha h)^n\right]^{m\ell}}$$ **(Equation 4-2)**

where:

$K(h)$	=	unsaturated hydraulic conductivity (cm/s)
K_s	=	saturated hydraulic conductivity (cm/s)
ℓ	=	pore-connectivity parameter [dimensionless], estimated by Mualem to be approximately 0.5 for many soils

Limited field investigation studies have shown that the vadose zone sediments in the 100 Areas contain a large gravel fraction (greater than 2-mm size). During the 1990s, as part of Westinghouse Hanford Company's environmental restoration project, moisture retention and unsaturated conductivity data were obtained in the laboratory for 100 Area sandy gravel sediments. Fifteen samples with a large gravel fraction were characterized for soil hydraulic properties (Table 4-1). These samples ranged in gravel content from 43 percent to 75 percent and can be used to represent the hydraulic properties for the gravel-dominated sequence in the 100 Areas.

Table 4-1. van Genuchten Parameters and Fitted Saturated Hydraulic Conductivity Data for 15 Sandy Gravel Samples

Sample	Operable Unit	Well Number	Depth (m)	% Gravel	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	α (1/cm)	n (-)	Fitted K_s (cm/sec)
2-1307	100-HR-3	199-D5-14	18.90	43	0.236	0.0089	0.0130	1.447	1.29E-04
2-1308	100-HR-3	199-D5-14	30.64	58	0.120	0.0208	0.0126	1.628	6.97E-05
2-1318	100-HR-3	199-D8-54A	15.54	60	0.124	0.0108	0.0081	1.496	1.67E-04
2-2663	100-BC-5	199-B2-12	8.20	61	0.135	0.0179	0.0067	1.527	6.73E-05
2-2664	100-BC-5	199-B2-12	24.84	73	0.125	0.0136	0.0152	1.516	1.12E-04
2-2666	100-BC-5	199-B4-9	21.49	71	0.138	0.00	0.0087	1.284	1.02E-04
2-2667	100-BC-5	199-B4-9	23.93	75	0.094	0.00	0.0104	1.296	1.40E-04
3-0570	100-KR-1	199-K-39	3.50	60	0.141	0.00	0.0869	1.195	2.06E-02
3-0577	100-FR-3	199-F5-43B	7.16	66	0.107	0.00	0.0166	1.359	2.49E-04
3-0686	100-FR-1	199-F5-51	6.49	55	0.184	0.00	0.0123	1.600	5.93E-04
3-1702	100-DR-2	199-D5-30	9.78	68	0.103	0.00	0.0491	1.260	1.30E-03
4-1086	100-K	199-K-110A	12.77	65	0.137	0.00	0.1513	1.189	5.83E-02
4-1090	100-K	199-K-111A	8.20	50	0.152	0.0159	0.0159	1.619	4.05E-04
4-1118	100-K	199-K-109A	10.30	66	0.163	0.00	0.2481	1.183	3.89E-02
4-1120	100-K	199-K-109A	18.90	63	0.131	0.0070	0.0138	1.501	2.85E-04

Source: RPP-20621, *Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment.*

K_s = saturated hydraulic conductivity

Standard laboratory procedures were used to analyze the gravelly samples. The moisture retention data for the fine fraction (less than 2 mm) and the drainage cycle of up to -1,000 cm of pressure head were measured using "Tempe" pressure cells; the remainder of the drainage data up to -15,000 cm was measured using the pressure plate extraction method ("Water Retention: Laboratory Methods" [Klute 1986]). Saturated hydraulic conductivities for the bulk samples (including gravels) were measured in the laboratory using constant-head permeameter. A variation of the unit gradient method ("Hydraulic Conductivity and Diffusivity: Laboratory Methods" [Klute and Dirksen 1986]; "Evaluation of van Genuchten-Mualem Relationships to Estimate Unsaturated Conductivity at Low Water Contents" [Khaleel et al. 1995]; "Variability of Gardner's α for Coarse-Textured Sediments"

[Khaleel and Relyea 2001]; "On the Hydraulic Properties of Coarse-Textured Sediments at Intermediate Water Contents" [Khaleel and Heller 2003]) was used to measure unsaturated hydraulic conductivities for the bulk samples. The laboratory measured data on <2-mm-size fraction were corrected for the gravel fraction ("Water Content" [Gardner 1986]; "Correcting Laboratory-Measured Moisture Retention Data for Gravels" [Khaleel and Relyea 1997]). No correction was needed for the saturated and unsaturated conductivities because these were measured on the bulk sample.

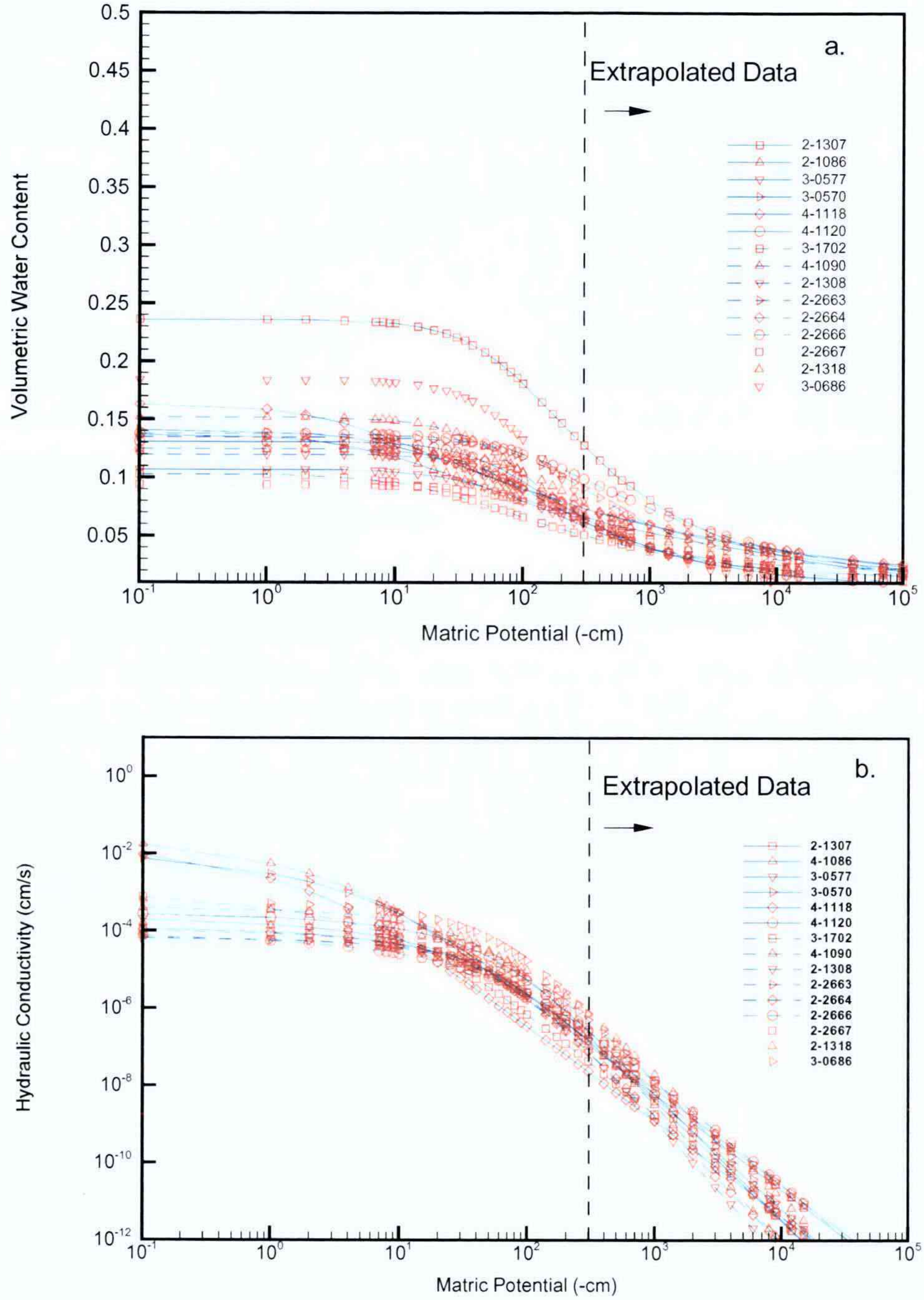
Estimated unsaturated hydraulic conductivities (based on saturated conductivity and the van Genuchten retention model) can often differ by up to several orders of magnitude with measured conductivities at the dry end (e.g., Khaleel et al. 1995). Therefore, a simultaneous fit of both laboratory-measured moisture retention and unsaturated conductivity data was used, and all five unknown parameters (θ_r, θ_s, α, n, and K_s), with m = 1-1/n (van Genuchten 1980), were fitted to the data via a code named RETention Curve (RETC) (EPA/600/2-91/065, *The RETC Code for Quantifying the Hydraulic Functions of Unsaturated Soils*). The pore-size distribution factor, ℓ (Mualem 1976), was kept fixed at 0.5 during the simultaneous fitting. The laboratory data for the 15 samples, following gravel-correction of the moisture retention data, are included in *Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment* (RPP-20621, Appendix A). The fitted moisture retention curves and unsaturated conductivity curves for the 15 samples for the gravel sequence are shown in Figure 4-1.

4.2 Aquifer Properties

The available information on saturated hydraulic conductivity and data sources are summarized in Table 4-2. The table provides the saturated conductivities for the 100 Areas based on field data (i.e., pumping tests and slug tests, primarily). If available, the analysis method used for the field data is noted in the table. In addition to values based on slug and pumping tests, a few conductivity estimates exist for laboratory-scale permeameter tests, which are not included in Table 4-2.

The hydraulic conductivities are grouped by the geologic unit (Hanford/Ringold); more data are available for the Ringold Formation than for the Hanford formation. The well locations (easting and northing) are identified in Table 4-2. For multiple entries of saturated hydraulic conductivity for the same location (Table 4-2), an average conductivity value should be used. The user is cautioned regarding the presence of outliers (Table 4-2); such outliers should be apparent whenever the overall statistics for each geologic unit are tabulated. For information regarding the test (screen) interval, the original sources should be consulted. Also note that Table 4-2 includes hydraulic conductivity estimates for some of the "699-" series wells, which are located in between the 100-D and 100-H Areas.

Site-specific data are not available for the 100 Areas on storage properties; however, some data are available for the Hanford and Ringold units based on field tests conducted in the 200 Areas. According to *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report* (PNL-10886) and *Summary and Evaluation of Available Hydraulic Property Data for the Hanford Site Unconfined Aquifer System* (PNL-8337), specific yield for the Hanford formation is estimated to range from about 0.1 to 0.3 and is expected to be higher for coarse, well-sorted gravel than for poorly sorted mixtures of sand and gravel. From previous work (PNL-10886, PNL-8337), specific yields of the poorly sorted sediments of the Ringold Formation are estimated to range from 0.05 to 0.2. In the absence of site-specific values, the preceding ranges can be used as initial estimates for 100-HR-3 OU storage properties.



Source: RPP-20621, *Far-Field Hydrology Data Package for the Integrated Disposal Facility Performance Assessment*.

Note: The symbols represent various samples, not experimental data.

Figure 4-1. Fitted Moisture Retention and Unsaturated Conductivity Curves for Fifteen Samples for the Gravel-Dominated Sequence

Table 4-2. 100 Areas Saturated Hydraulic Conductivities (after SGW-40781, Rev. 1)

Well Number	Easting (m)	Northing (m)	K_s (ft/day)	K_s (m/day)	Formation	Test Type/ Analysis Method	Reference
199-D2-11	573328.2	151120.7	205	62.50	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D2-6	573000.2	151119.9	40	12.19	Ringold	Slug	DOE/RL-93-43
199-D4-1	572752.8	151558.9	76	23.23	Ringold	Pumping/ISOAQX and WTAQ3##	PNNL-13349
199-D4-11	572768.9	151554.1	40	12.26	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-12	572771.6	151562.1	73	22.38	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-2	572768.4	151544	55	16.71	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-2	572768.4	151544	61	18.64	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-3	572766.1	151546.1	57	17.38	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-3	572766.1	151546.1	61	18.66	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-4	572754.6	151571.6	105	32.10	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-7	572760.9	151551.3	55	16.68	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-8	572763.3	151552.6	36	10.90	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D4-9	572758.2	151543.3	53	16.25	Ringold	Pumping/ISOAQX and WTAQ3	PNNL-13349
199-D5-102	573428.2	151340.2	237	72.26	Ringold	Pumping/Cooper-Jacob	SGW-38757

Table 4-2. 100 Areas Saturated Hydraulic Conductivities (after SGW-40781, Rev. 1)

Well Number	Easting (m)	Northing (m)	K_s (ft/day)	K_s (m/day)	Formation	Test Type/ Analysis Method	Reference
199-D5-103	573505.9	151460.9	101	30.79	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-104	573265.5	151422.4	236	71.95	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-119	573306.5	151415.1	156	47.56	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-120	573377.2	151406.8	177	53.9	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-121	573429.9	151399.3	28	8.54	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-122	573302.3	151346.1	167	50.92	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-14	573789.6	151788	30	9.14	Ringold	Slug	DOE/RL-93-43
199-D5-15	573738.6	151673.8	30	9.14	Ringold	Slug	DOE/RL-93-43
199-D5-16	573917.5	151652.5	10	3.05	Ringold	Slug	DOE/RL-93-43
199-D5-17	573730.5	151322.8	10	3.05	Ringold	Slug	DOE/RL-93-43
199-D5-18	573861.7	151325.2	60	18.29	Ringold	Slug	DOE/RL-93-43
199-D5-19	573849.1	151243.2	40	12.19	Ringold	Slug	DOE/RL-93-43
199-D5-20	573240	152030.2	40	12.19	Ringold	Slug	DOE/RL-93-43
199-D5-97	573250.1	151302.5	158	48.17	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-98	573369.6	151272.4	169	51.52	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D5-99	573349.6	151402	92	28.05	Ringold	Pumping/Cooper-Jacob	SGW-38757
199-D8-3	573942.4	152347.9	1837	560	Ringold	Pumping	PNL-10886
199-D8-53	573889.9	152452.3	530	161.54	Ringold	Slug	DOE/RL-93-43
199-D8-55	573621	152364.3	20	6.10	Ringold	Slug	DOE/RL-93-43
199-D8-54A	573781.1	152408.0	400	121.9	Ringold	Slug	DOE/RL-93-43

Table 4-2. 100 Areas Saturated Hydraulic Conductivities (after SGW-40781, Rev. 1)

Well Number	Easting (m)	Northing (m)	K_s (ft/day)	K_s (m/day)	Formation	Test Type/ Analysis Method	Reference
199-K-10	568912.8	146628.1	52	16	Ringold	Pumping/Cooper-Jacob	PNL-10886
199-K-10	568912.8	146628.1	53	16.16	Not reported	Pumping/Cooper-Jacob	PNL-8337
199-K-106A	568697.4	146502.4	9	2.68	Ringold	Slug/Bouwer-Rice	WHC-SD-EN-DP-090
199-K-107A	568579.9	146468.8	5	1.55	Ringold	Slug/Bouwer-Rice	WHC-SD-EN-DP-090
199-K-108A	568687.2	146396.1	3	0.98	Ringold	Slug/Bouwer-Rice	WHC-SD-EN-DP-090
199-K-110A	569230	146677.9	4	1.10	Ringold	Slug/Bouwer-Rice	WHC-SD-EN-DP-090
199-K-110A	569230	146677.9	32	9.79	Ringold	Slug/Bouwer-Rice	WHC-SD-EN-TI-221
199-K-111A	569308.2	146968.9	26	8.00	Ringold	Slug/Bouwer-Rice	WHC-SD-EN-DP-090
199-K-111A	569308.2	146968.9	27	8.35	Ringold	Slug/Bouwer-Rice	WHC-SD-EN-TI-221
199-K-18	569353.7	147400.8	9	2.80	Ringold	Pumping/Cooper-Jacob	Edrington 1996
199-K-19	569458.5	147386.6	6	1.83	Ringold	Pumping/Cooper-Jacob	Edrington 1996
199-K-20	569520.5	147687.2	111	33.84	Ringold	Pumping/Cooper-Jacob	Edrington 1996
199-K-21	569769.9	147932.1	16	5.00	Ringold	Pumping/Cooper-Jacob	Edrington 1996
199-K-22	570023.7	148097.4	3	0.88	Ringold	Pumping/Cooper-Jacob	Edrington 1996
199-K-32A	569024.2	147006.7	80	24.38	Ringold	Slug/Bouwer-Rice	DOE/RL-93-79
199-K-33	568573.7	146713.3	19	5.79	Ringold	Slug/Bouwer-Rice	DOE/RL-93-79
199-K-34	568605.8	146501.9	68	20.73	Ringold	Slug/Bouwer-Rice	DOE/RL-93-79
199-K-35	568832.3	146110.7	124	37.80	Ringold	Slug/Bouwer-Rice	DOE/RL-93-79
199-K-36	569373.8	146390.7	87	26.52	Ringold	Slug/Bouwer-Rice	DOE/RL-93-79
199-K-37	570216.2	148226.5	145	44.20	Ringold	Slug/Bouwer-Rice	DOE/RL-93-79
199-N-119	571364.5	149968.3	14	4.3	Ringold	Slug/Bouwer-Rice	PNNL-16894

Table 4-2. 100 Areas Saturated Hydraulic Conductivities (after SGW-40781, Rev. 1)

Well Number	Easting (m)	Northing (m)	K_s (ft/day)	K_s (m/day)	Formation	Test Type/ Analysis Method	Reference
199-N-119	571364.5	149968.3	22	6.7	Ringold	Slug/Type curve Butler	PNNL-16894
199-N-120	571366.2	149970.8	17	5.3	Ringold	Slug/Bouwer-Rice	PNNL-16894
199-N-120	571366.2	149970.8	21	6.4	Ringold	Slug/Bouwer-Rice	PNNL-16894
199-N-121	571368.3	149973.3	12	3.7	Ringold	Slug/Bouwer-Rice	PNNL-16894
199-N-121	571368.3	149973.3	12	3.8	Ringold	Slug/Bouwer-Rice	PNNL-16894
199-H3-2C	577632.1	152750.3	39	11.9	Ringold	Pumping	PNL-6728
199-H4-15C(R)	577907.7	153060.0	350	106.7	Ringold	Pumping	PNL-6728
199-H4-15C(Q)	577907.7	153060.0	0.14	0.04	Ringold	Pumping	PNL-6728
699-91-46	575911.0	151156.6	790	240.85	Hanford	Slug/Bouwer-Rice	DOE/RL-93-43
699-93-48	575094.1	151795.3	60	18.29	Hanford	Slug/Bouwer-Rice	DOE/RL-93-43
699-96-43	576761.5	152605.3	50	15.24	Hanford	Slug/Bouwer-Rice	DOE/RL-93-43
199-D2-5	573812.3	151148.2	182	55.5	Hanford	Pumping	PNL-10886
199-H3-2A	577624.6	152750.1	1900	579.12	Hanford	Pumping	PNL-6471
199-H3-2A	577624.6	152750.1	1900	579.1	Hanford	Pumping	PNL-6728
199-H3-2B	577628.3	152757.2	100	30.49	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H4-10	577827.2	153155.8	3445	1050.04	Hanford	Pumping	PNL-6471
199-H4-10	577827.2	153155.8	5900	1798.32	Hanford	Pumping	PNL-6728
199-H4-10	577827.2	153155.8	5940	1810.51	Hanford	Pumping	PNL-6471
199-H4-10	577827.2	153155.8	5878	1792.00	Hanford	Pumping	PNL-10886
199-H4-11	578141.9	152728.4	50	15.24	Hanford	Pumping	PNL-6471
199-H4-11	578141.9	152728.4	70	21.34	Hanford	Slug/Bouwer-Rice	PNL-6728

Table 4-2. 100 Areas Saturated Hydraulic Conductivities (after SGW-40781, Rev. 1)

Well Number	Easting (m)	Northing (m)	K_s (ft/day)	K_s (m/day)	Formation	Test Type/ Analysis Method	Reference
199-H4-11	578141.9	152728.4	71	21.64	Hanford	Pumping	PNL-6471
199-H4-12A	578009.2	152912.7	134	41	Hanford	Pumping/Theis	PNL-10886
199-H4-12A	578009.2	152912.7	210	64.01	Hanford	Pumping	PNL-6728
199-H4-12A	578009.2	152912.7	213	64.92	Hanford	Pumping	PNL-6471
199-H4-12A	578009.2	152912.7	376	114.60	Hanford	Pumping	PNL-6471
199-H4-12B	578004.4	152918.5	50	15.24	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H4-13	578219.3	152595.3	420	128.05	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H4-14	577803.7	152752.4	250	76.22	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H4-15A	577904.3	153053.4	109	33.22	Hanford	Pumping	PNL-6471
199-H4-15A	577904.3	153053.4	182	55.47	Hanford	Pumping	PNL-6471
199-H4-15A	577904.3	153053.4	187	57	Hanford	Pumping	PNL-10886
199-H4-15A	577904.3	153053.4	195	59.44	Hanford	Pumping	PNL-6471
199-H4-15A	577904.3	153053.4	200	60.96	Hanford	Pumping	PNL-6728
199-H4-15B	577899.6	153059.5	460	140.24	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H4-16	577981.9	152591.6	220	67.07	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H4-18	578018.3	152756.5	80	24.39	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H4-3	577940.5	152858.5	171	52.00	Hanford	Pumping	PNL-10886
199-H4-45	578156.4	152433.4	100	30.48	Hanford	Slug	DOE/RL-93-43
199-H4-46	577883.9	152439.9	120	36.58	Hanford	Slug	DOE/RL-93-43
199-H4-47	577891.2	152553.3	90	27.43	Hanford	Slug	DOE/RL-93-43
199-H4-48	577792.7	152620.2	80	24.38	Hanford	Slug	DOE/RL-93-43

Table 4-2. 100 Areas Saturated Hydraulic Conductivities (after SGW-40781, Rev. 1)

Well Number	Easting (m)	Northing (m)	K_s (ft/day)	K_s (m/day)	Formation	Test Type/ Analysis Method	Reference
199-H4-49	577713.8	152445.2	90	27.43	Hanford	Slug	DOE/RL-93-43
199-H4-7	577804.1	152890.8	70	21.34	Hanford	Slug/Bouwer-Rice	PNL-6728
199-H5-1	577650.1	152257.7	110	33.54	Hanford	Slug/Bouwer-Rice	DOE/RL-93-43
199-H6-1	578236.6	152247.6	70	21.34	Hanford	Slug	DOE/RL-93-43

The references cited in this table are included in the reference list in Chapter 11.

ISOAQX and WTAQ3 are automated computer programs for analyzing aquifer drawdown data. ISOAQX is described in "A Reassessment of Ground Water Flow Conditions and Specific Yield at Borden and Cape Cod" (Grimestad 2002). WTAQ3 is described in "Flow to a Well of Finite Diameter in a Homogeneous, Anisotropic Water-Table Aquifer" (Moench1997).

K_s = saturated hydraulic conductivity

4.3 Transport Properties

Estimates for contaminant Kd for the key COC (i.e., chromium), sediment bulk density, and macrodispersivity are needed for the 100 Areas. Chromium Kd values are documented in several reports (e.g., DOE/RL-96-17, *Remedial Design Report/Remedial Action Work Plan for the 100 Area*; PNL-7660, *Compilation of Data to Estimate Groundwater Migration Potential for Constituents in Active Liquid-Discharges at the Hanford Site*; and WHC-SD-EN-TI-302, *Speciation and Transport Characteristics of Chromium in the 100-D/H Areas of the Hanford Site*). Most recent Hanford Site assessments have primarily relied on the Kd estimates documented in *Geographic and Operational Site Parameters List (GOSPL) for Hanford Assessments* (PNNL-14725).

As detailed in PNNL-14725 and *Geochemical Processes Data Package for the Vadose Zone in the Single-Shell Tank Waste Management Areas at the Hanford Site* (PNNL-16663), best-estimate Kd values for contaminated sediments (those impacted by waste) were compiled for six waste chemistry/source categories:

- Very acidic
- Very high salt/very basic
- Chelates/high salts
- Low organic/low salt/low neutral
- Integrated disposal facility vitrified waste
- Integrated disposal facility cementitious waste.

The Kd values for the fourth class (low organic/low salt/low neutral) are representative for the 100 Areas and are provided in Table 4-3.

Table 4-3. Recommended Distribution Coefficient for Hexavalent Chromium for 100 Areas Groundwater Transport Model

Sediment Type	Gravel-Dominated (>60% Gravel)	Sandy Gravel	Gravelly Sand	Sand-Dominated	Silt-Dominated	Carbonate-Dominated
% (wt.) gravel	67.6	50	30	2	0.4	16.7
Distribution coefficient	0	0	0	0	0	0

Table 4-4 provides the bulk density estimates and their variability for Hanford and Ringold units. These values derived from *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis* (PNNL-14702, Tables 17 and 27 in Appendix B).

Table 4-4. Recommended Bulk Density Values for Hanford and Ringold Units

Formation	Number of Samples	Bulk Density (g/cm^3) Low	High	Mean	Standard Deviation
Hanford	26	1.60	2.30	1.91	0.21
Ringold	18	1.63	2.17	1.90	0.15

Source: PNNL-14702, *Vadose Zone Hydrogeology Data Package for the 2004 Composite Analysis.*

Macrodispersivity is a scale-dependent parameter and can only be determined from inverse modeling of tracer tests on the scale of interest. Because very few such large-scale tracer tests have been conducted, and none have been conducted at the Hanford Site, the macrodispersivity values used in the groundwater transport model were not based on Hanford Site data. However, longitudinal macrodispersivity for the Hanford formation and Cold Creek gravel unit is considered to generally lie within the range of 60 to 120 m (197 to 394 ft) for a sand and gravel aquifer, as determined in "Field Study of a Long and Very Narrow Contaminant Plume" (van der Kamp et al. 1994). The recommended values for longitudinal dispersivity and transverse dispersivity for use for groundwater transport modeling in the 100 Areas are listed in Table 4-5: these values are recommended values, only, and actually values used may vary (a) as a result of the scale of the simulation and (b) in order to ensure that values used in the groundwater transport model should also satisfy the grid Peclet number and Courant number constraints.

Table 4-5. Recommended Dispersivity Values for 100 Areas Groundwater Transport Model

Formation Type	Longitudinal Macrodispersivity (m)	Transverse Macrodispersivity (m)
Hanford/Pre-Missoula gravels	– 62.5	– 12.5
– Ringold gravels	– 30	– 6

5 Model Implementation

5.1 Background

Groundwater flow models have been used at the 100 K, 100 D, and 100 H Areas (DOE/RL-96-84, *Remedial Design Report and Remedial Action Work Plan for the 100-HR-3 and 100-KR-4 Groundwater Operable Units' Interim Action*) to support design of pump-and-treat interim remedies and to evaluate the performance of the pump-and-treat systems. These groundwater flow models were constructed to simulate patterns of groundwater flow and other hydraulic features local to each operable unit (OU) and, as such, the domains of these models were of limited spatial extent. As modeling needs increased over time, efforts were undertaken to develop a groundwater model that unified the simulations for all 100 Area groundwater operable units. The expansion of the model domain over time to encompass the 100 Area OUs occurred in several phases, as follows:

- First, because the size and influence of the 100 Area groundwater pump-and-treat remedies at 100-K, 100-D and 100-H increased over time, a single, two-dimensional groundwater flow model was developed that encompassed the 100-K, 100-N, 100-D, and 100-H Areas (DOE/RL-2006-75, *Supplement to the 100-HR-3 and 100-KR-4 Remedial Design Report and Remedial Action Workplan for the expansion of the 100-KR-4 Pump and Treat System*). At this time, there were no proposed or actual remedial activities at 100-B/C or 100-F that required model simulation of those areas.

- Second, pump-and-treat remedial process optimization (RPO) efforts led by CHPRC during Calendar Years 2008 and 2009 in 100-HR-3 and 100-KR-4 required contaminant transport simulations to develop projections of hexavalent chrome distributions and evaluate plume migration patterns and attainment of river protection and aquifer cleanup goals. For that purpose the two-dimensional groundwater flow model was coupled with a contaminant transport model (SGW-46279, *Conceptual Framework and Numerical Implementation of the 100 Areas Groundwater Flow and Transport Model, Rev. 0*). The results of these RPO modeling efforts in 100-HR-3 are described in SGW-40044 (*100-HR-3 Remedial Process Optimization Modeling Technical Memorandum.*) The *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan* (DOE/RL-2008-46, *Integrated 100 Area Remedial Investigation/Feasibility Study Work Plan Draft A*) described the strategy developed for making final decisions to complete cleanup along the River Corridor. A series of addenda to the work plan outlined the goals and strategy data collection and analyses for each 100 Area OU to develop the remedial investigation/feasibility (RI/FS) studies.

- Third, as data became available indicating that a three-dimensional (3D) model would be more suitable for representing the partial penetration of many pumped and monitoring wells, and vertical differences in contaminant distribution, the two-dimensional (2D) (i.e., single model layer) model was expanded to 3D, comprising four (4) model layers. The lateral extents of the model continued to encompass only 100-K, 100-N, 100-D and 100-H Areas.

- Finally, to meet the RI/FS needs for each 100 Area OU, this 3D groundwater model was expanded to encompass 100-B/C and 100-F – i.e., now encompassing all 100 Area OUs - simulating groundwater flow as three-dimensional to explicitly represent the Hanford formation and Ringold Unit E Formation that comprise the unconfined aquifer across the 100 Areas.

As a result, the current 100 Area Groundwater Model (100AGWM) simulates saturated aquifer conditions and contaminant transport in 100-B/C, 100-K, 100-D, 100-H, 100-N and 100-F Areas.

5.2 Software

The groundwater flow model is constructed using the U.S. Geological Survey (USGS) three-dimensional modular groundwater flow model, MODFLOW ("A Modular Three-Dimensional Finite-Difference Ground-Water flow Model" [McDonald and Harbaugh, 1988]; User Documentation for MODFLOW 96, An Update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model [Harbaugh and McDonald, 1996]; "MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model – User Guide to Modularization Concepts and the Ground-Water Flow Process" [Harbaugh et al., 2000]; "MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model – The Ground-Water Flow Process" [Harbaugh, 2005]).

The MODFLOW code was selected because it has the necessary simulation capabilities, is relatively simple to use, and can be executed on a variety of computers and operating systems without modification. MODFLOW simulates groundwater flow using the block-centered, finite-difference approach (McDonald and Harbaugh, 1988). The finite-difference approach can simulate two-dimensional groundwater flow using a single layer to represent the aquifer, or three-dimensional groundwater flow using a series of model layers that may represent individual aquifers or aquitards, or that may be used to provide vertical discretization detail within thick aquifers or aquitards. Layers can be simulated as unconfined (e.g., water table aquifers), confined, or as convertible between unconfined and confined conditions.

The following additional programs were used in addition to MODFLOW:

- Contaminant Transport: MT3DMS Version 5.3 (Zheng, 2010) - the second generation of the modular, three-dimensional transport model MT3D, that is distributed with expanded wide range of transport simulation capabilities - was used to simulate contaminant plume migration throughout the 100AGWM, and the impacts of the operation of the extraction and injection wells, and provide a basis for comparative remedy analyses in each OU as part of the RPO and RI/FS processes.
- Calibration: PEST (Doherty, 2010) is an advanced software package for model calibration, parameter estimation, and predictive uncertainty analysis that was used to assist in the groundwater flow model calibration. PEST Version 11.3 was used in this work.
- GeoData Management: An ArcGIS (ESRI ArcMap 9.3) database was developed in support of the 100 Areas MODFLOW modeling to provide a focused geodatabase for the spatial information included in the model. This database also provided additional vector and raster information for effective data management and mapping of model inputs and simulation results.

5.2.1 Approved Software

The following software was used to perform calculations and was approved and compliant with PRC-PRO-IRM-309 (PRC-PRO-IRM-309, Controlled Software Management). These software are managed under the following documents consistent with PRC-PRO-IRM-309:

- CHPRC-00257 Rev 1, MODFLOW and Related Codes Functional Requirements Document,
- CHPRC-00258 Rev 2, MODFLOW and Related Codes Software Management Plan
- CHPRC-00259 Rev 1, MODFLOW and Related Codes Software Test Plan
- CHPRC-00260 Rev 2, MODFLOW and Related Codes Acceptance Test Report, and
- CHPRC-00261 Rev 1, MODFLOW and Related Codes Requirements Traceability Matrix.

CHPRC-00258 Rev 2 distinguishes between safety software and support software based on whether the software managed calculates reportable results or provides run support, visualization, or other similar functions. Brief descriptions of the software are provided below.

5.2.2 Descriptions

5.2.2.1 MODFLOW (Controlled Calculation Software)

- Software Title: MODFLOW-2000 (Harbaugh et al. 2000: Open File Report 00-92, MODFLOW-2000, the US. Geological Survey Modular Ground-water model -- User Guide to Modularization Concepts and the Ground- Water Flow); solves transient groundwater flow equations using the finite-difference discretization technique.
- Software Version: Version 1.19.01 modified by S.S. Papadopulos and Associates, Inc. (SSP&A) to address dry cell issues and to add more capabilities; approved as CHPRC Build 0004 using executable mf2k-mst-0004dp (compiled to default double precision for real variables).
- Hanford Information Systems Inventory (HISI) Identification Number: 2517 (Safety Software, graded Level C).
- Workstation type and property number (from which software is run):
    - S.S. Papadopulos and Assoc, Inc, FE363.

5.2.2.2 MT3DMS (Controlled Calculation Software)

- Software Title: MT3DMS (Zheng and Wang 1999), MT3DMS: A Modular Three-dimensional Multispecies Transport Model for Simulation of Advection, Dispersion, and Chemical Reactions of Contaminants in Groundwater Systems; Documentation and User's Guide); MT3DMS V5.3 Supplemental User's Guide [Zheng 2010])
- Software Version: Version 5.3 modified by S.S. Papadopulos and Associates, Inc. (SSP&A) for minimum saturated thickness; approved as CHPRC Build 0004 using executable mt3d-mst-0004dp (compiled to default double precision for real variables).
- HISI Identification Number: 2518 (Safety Software, graded Level C).
- Workstation type and property number (from which software is run):
    - S.S. Papadopulos and Assoc, Inc, FE363.

5.2.3 Software Installation and Checkout

Safety Software (CHPRC Build 0004 of MODFLOW-2000-SSPA) is checked out in accordance with procedures specified in CHPRC-00258 Rev 2. Executables are obtained from the CHPRC software owner who maintains the configuration managed copies in MKS Integrity™, installation tests identified in CHPRC-00259 Rev 1 performed and successful installation confirmed, and Software Installation and Checkout Forms are required and must be approved for installations used to perform model runs. Approved Users are registered in HISI for safety software.

1.1.1 Statement of Valid Software Application

- The software identified above was used consistent with intended use for CHPRC as identified in CHPRC-00257 Rev 1 and is a valid use of this software for the problem addressed in this application.
- The software was used within its limitations as identified in CHPRC-00257 Rev 1.

5.2.4 Support Software

Support software and single-purpose software was used to manage and develop datasets to be used by the model as well as pre- and post-process model input/output files. A complete list and brief description of the support software used for these purposes is listed in Table 5-1 . Software with a trademark designation is commercial software. Software listed without a trademark has been developed internally and the resulting calculation products were approved through quality assurance and technical review. Electronic copies of all utilities are included in the 100AGW model archive in the *Environmental Model*

Management Archive (EMMA), the model configuration management system required under CHPRC-00805 Rev. 0 (*Quality Assurance Project Plan for Modeling).*

Table 5-1. Support Software.

Purpose	Software	Description
DIS Package	*CalcLayerBottomElev.exe*	Calculation of model layer bottom elevations from interpolated data to be included MODFLOW DIS Package.
LPF Package	*Fieldgensrc.exe*	Development of the hydraulic conductivity field for MODFLOW LPF Package.
RIV Package	*1_Irreg2Reg.exe*	Generation of regularly spaced points along the polyline representing the Columbia River.
	2_Irreg2Regz.exe	Interpolation of river stage elevation at the regularly spaced points.
	3_xyz2HdepN.exe	Interpolation of river stage elevation at the center of each MODFLOW RIV cell.
	4_RiverPackage.exe	Development of MODFLOW RIV Package with interpolated river stage elevation for top model layer cells and all stress periods.
	6_RIVRewrite.exe	Development of the complete MODFLOW RIV Package for all layers and stress periods, assigning each river cell to the appropriate model layer based on layer and river stage/bottom elevations.
	7_ModifyRIV.exe	Update river bed conductance along defined river reaches.
MNW2 Package	*Allocateqwell.exe*	Development of MODFLOW MNW2 Package by processing well screen information and pumping data.
CHD (Constant Head) Package	*calcchd.exe*	Development of MODFLOW CHD Package from water level data obtained from the Central Plateau Model (CP-47361, *Model Package Report: Central Plateau Groundwater Model Version 3.3.*)
GHB (General Head Boundary) Package	*CalcRiverBasedGHB.exe*	Development of MODFLOW GHB Package using river stage data and interpolated aquifer hydraulic head data at the western and southeastern boundary.
General use	Surfer™[1]	Data interpolation for visualization and model quality assurance purposes.
General use	*Groundwater Vistas™*[2]	Data interpolation for visualization and model quality assurance purposes.
General use	*ArcGIS™*[3]	Data interpolation for visualization and model quality assurance purposes.

[1] Surfer is a trademark of Golden Software, Golden, CO.

[2] Groundwater Vistas is a trademark of Environmental Simulations Incorporated, Reinholds, PA.

[3] ArcGIS is a trademark of ESRI, Redlands, CA.

Table 5-1. Support Software.

Purpose	Software	Description
Post-Processing Utilities	*Makehds.exe*	Append the model-calculated hydraulic head distribution at the end of the first stress period to the HDS MODFLOW output file.
	Headtarg_s.exe, Headtarg_d.exe	Retrieve and interpolate simulated hydraulic heads at monitoring well locations and corresponding screened intervals, allowing for dry model cells.
	Gradtarg_s.exe, Gradtarg_d.exe	Calculate magnitude and direction of hydraulic gradients based on model simulated hydraulic heads.
	CalcGapFlux.exe	Calculate water flux exchanged between the 100 Areas and the Central Plateau through the Constant Head boundaries in the Western Gap and Gable Gap.

Electronic copies of (a) modeling software; (b) model input/output files; (c) input data; and (d) pre-/post-processing utilities and other support software mentioned throughout this report are archived in EMMA.

5.3 Model Domain

The 100AGWM groundwater model domain is shown in Figure 5.1. The 100 Areas are located within the portion of the Hanford Site between Gable Mountain and Gable Butte in the south and the Columbia River in the north and northeast. The domain is constricted by basalt sub-crops along the southern boundary. There are two gaps along the southern boundary between the basalt sub-crops; the Western Gap and the Gable Gap. Water generally flows through the gaps into the 100 Areas and discharges to the Columbia River. Low to moderate areal recharge contributes to the water budget across the model domain.

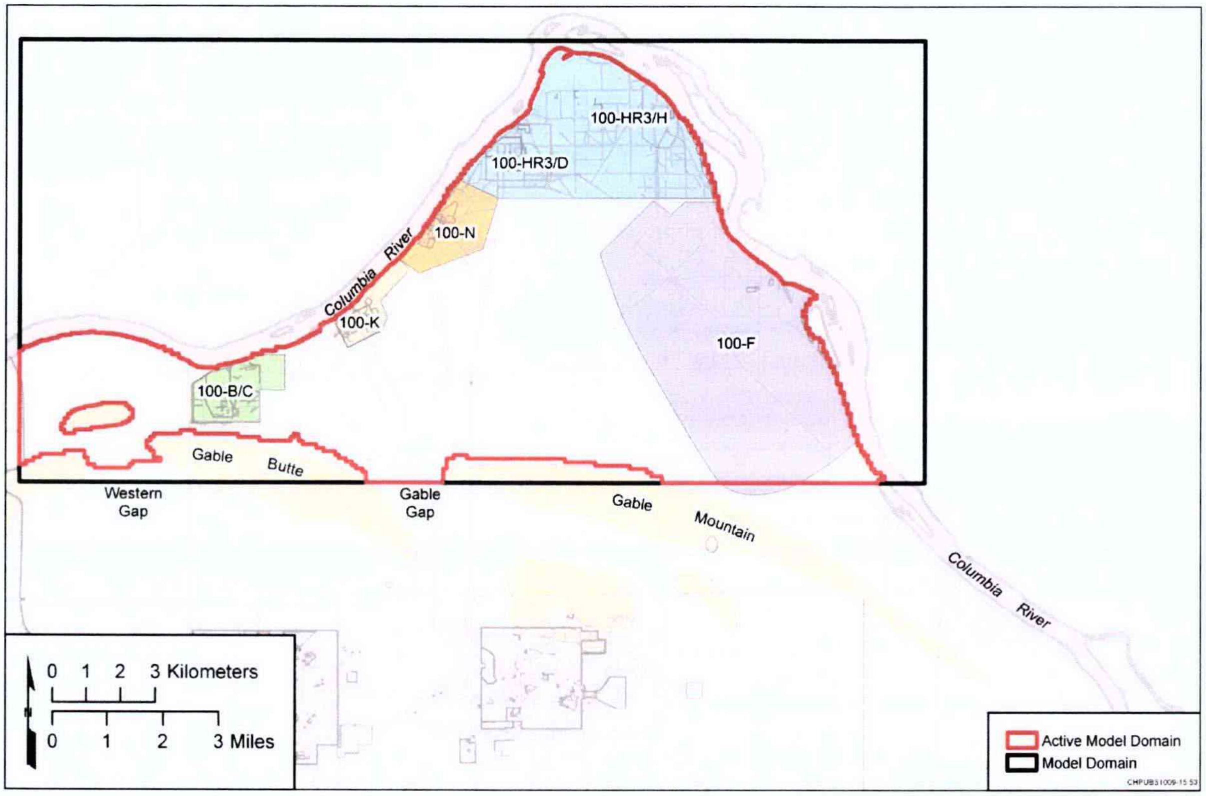


Figure 5-1. Model Domain and Location of the 100 Area Groundwater OUs.

The conceptual model for the 100AGWM, as described in detail in Section 3, considers saturated porous flow through the unconfined flow system. The unconfined flow system consists of the Hanford formation and the Ringold E Formation, where present. The base of the model is assumed to be the top of the Ringold Upper Mud (RUM) where present and the top of the basalt where the RUM is absent, which typically occurs in the southern portions of the model approaching Gable Butte. Throughout much of the western half of the modeled area (including 100-K and 100-D), the water table lies within the Ringold Unit E sands, whereas toward the east and north of the modeled area (including 100-H and 100-F), the water table lies within the Hanford formation sands and gravels. In the vicinity of 100-B/C the water table fluctuates between the two formations. Water enters the system through areal recharge and from the Columbia River. Additionally, water from the Central Plateau enters the 100 Areas through the Western Gap and the Gable Gap. Water exits the system primarily by discharging to the Columbia River.

5.4 Spatial Discretization

5.4.1 Horizontal Discretization

Figure 5-2 illustrates the spatial extent of the 100AGWM: the locations of the 100-B/C, 100-K, 100-N, 100-D, 100-H and 100-F Areas are also shown. The 100-HR-3 OU encompasses the 100-D and 100-H Areas, which are treated as a single groundwater OU for the purposes of the remedy design. Although earlier versions of the model finite-difference grid were rotated, so that the northern and eastern boundaries of the flow model were parallel to and abut the Columbia River, the expanded final domain as shown in Figure 5-3 is not rotated. The model extends southward, toward Gable Butte and Gable Mountain. The model grid spacing is relatively coarse (100 m [328 ft]) throughout much of the model domain, but it is refined (15 m [49 ft]) in the area of the Operable Units in support of remedy evaluations.

The model grid is shown in Figure 5-3. The model domain has the following spatial extent and boundaries:

Approximate horizontal extent (rectangular region):

- 12.8 km north-south
- 26.4 km east-west
- The lower left corner of the model domain is located at: Easting 559125 m, and Northing 141970 m in the Washington State Coordinate System: NAD_1983_StatePlane_Washington_South_FIPS_4602

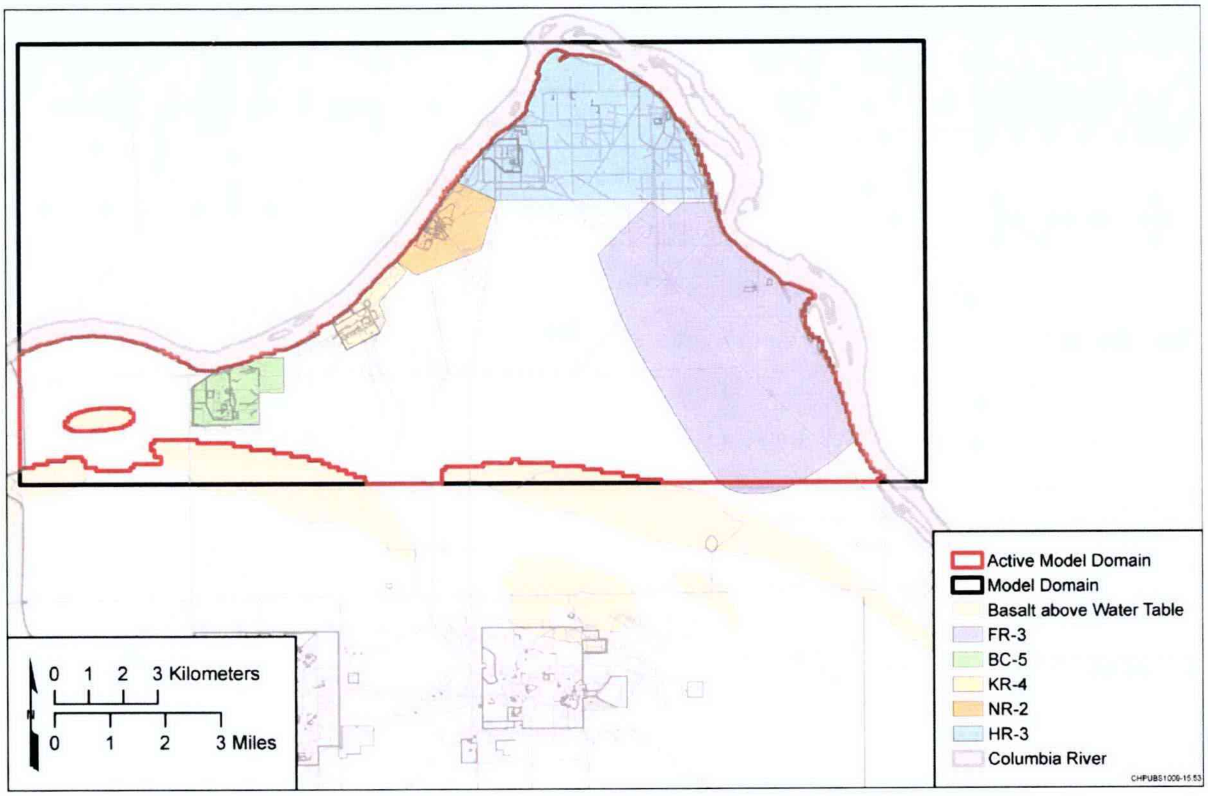


Figure 5-2. Spatial Extent of the 100 Area Model.

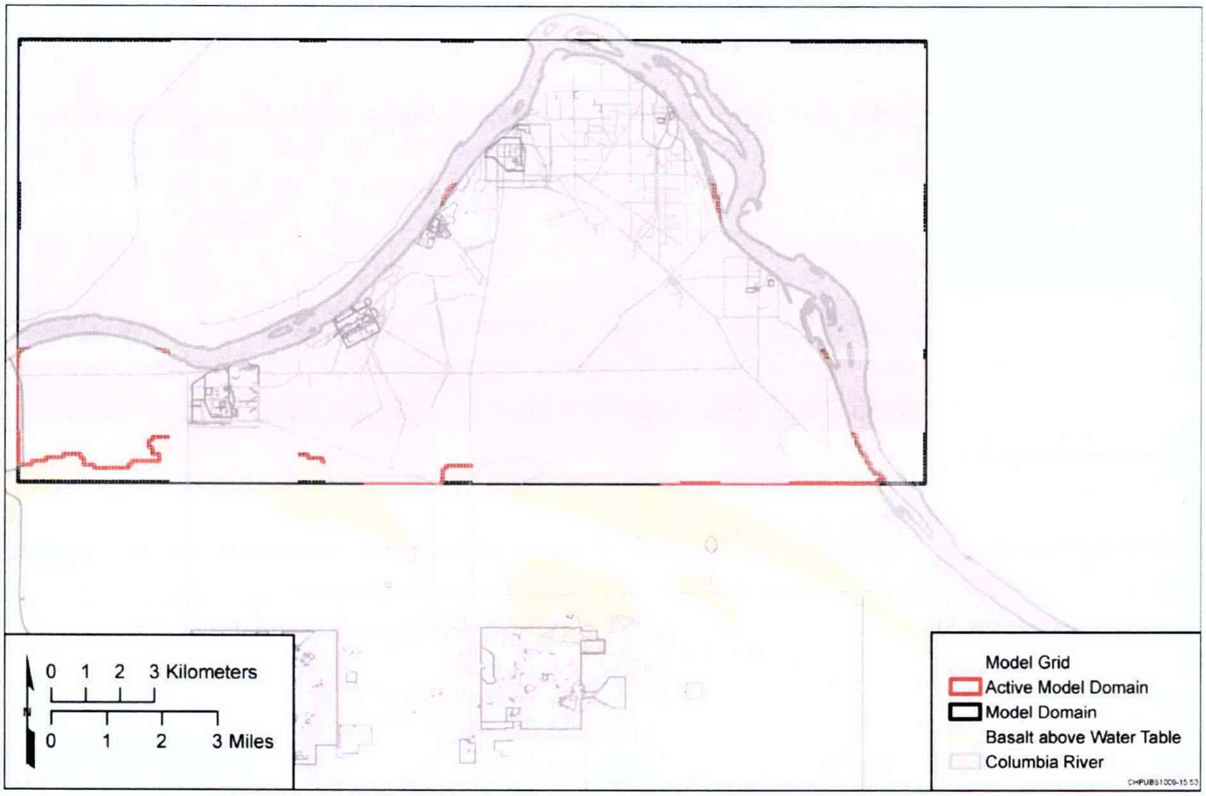


Figure 5-3. 100AGW Model Grid.

5.4.2 Vertical Discretization

Groundwater flow is simulated as three-dimensional (3D) using four layers. These layers represent the Hanford formation (always present in Layer 1, across the entire model domain) and the Ringold E Formation (typically represented by Layers 2 through 4, except east of 100-D where it is absent and therefore all model layers represent the Hanford formation).

The base of the model is assumed to be the top of the Ringold Upper Mud (RUM) where present and the top of the basalt where the RUM is absent, which typically occurs in the southern portions of the model approaching Gable Butte. The geologic characterization compiled as part of the Model Data Packages (SGW-40781 Rev. 0, *100-HR-3 Remedial Process Optimization Modeling Data Package*; SGW-41213 Rev. 0, *100-KR-4 Remedial Process Optimization Modeling Data Package*; SGW-44022 Rev. 0, *Geohydrologic Data Package in Support of 100-BC-5 Modeling*; SGW-47040 Rev. 0, *Geohydrologic Data Package in Support of 100-FR-3 Modeling*) appears to depict a reasonably abrupt lateral transition from areas where the water table lies dominantly within the Ringold Unit E in the west and south of the model domain to areas where the water table lies dominantly within the Hanford formation sands and gravels in the east and north of the model domain, that occurs between the 100-D and 100-H areas.

The development of the model layer bottom elevation distribution is based on the mapped surfaces for the Hanford-Ringold E contact and the top of the RUM/basalt; interpolation of those surfaces to the model grid; and a rule-based systematic procedure to determine layer thickness from the interpolated data. Details on the interpolation of each surface and the development of model layer elevations are provided in the following subsections.

5.4.2.1 Development of Top of Basalt Surface

The top of basalt defines the lowermost boundary of the 100 Area Model in areas where the RUM is absent. The elevations of the basalt surface were received from Intera, Inc – a Hanford contractor – in an ASCII Grid format (filename "basalt_ellensburg_top_2010update_m.ascii"). This dataset was converted into an ESRI shapefile and interpolated to the model grid. The interpolated surface was exported to a MODFLOW-compatible ASCII array that allows the dataset to be easily processed with existing data processing utilities. The basalt top elevations are shown in Figure 5-4.

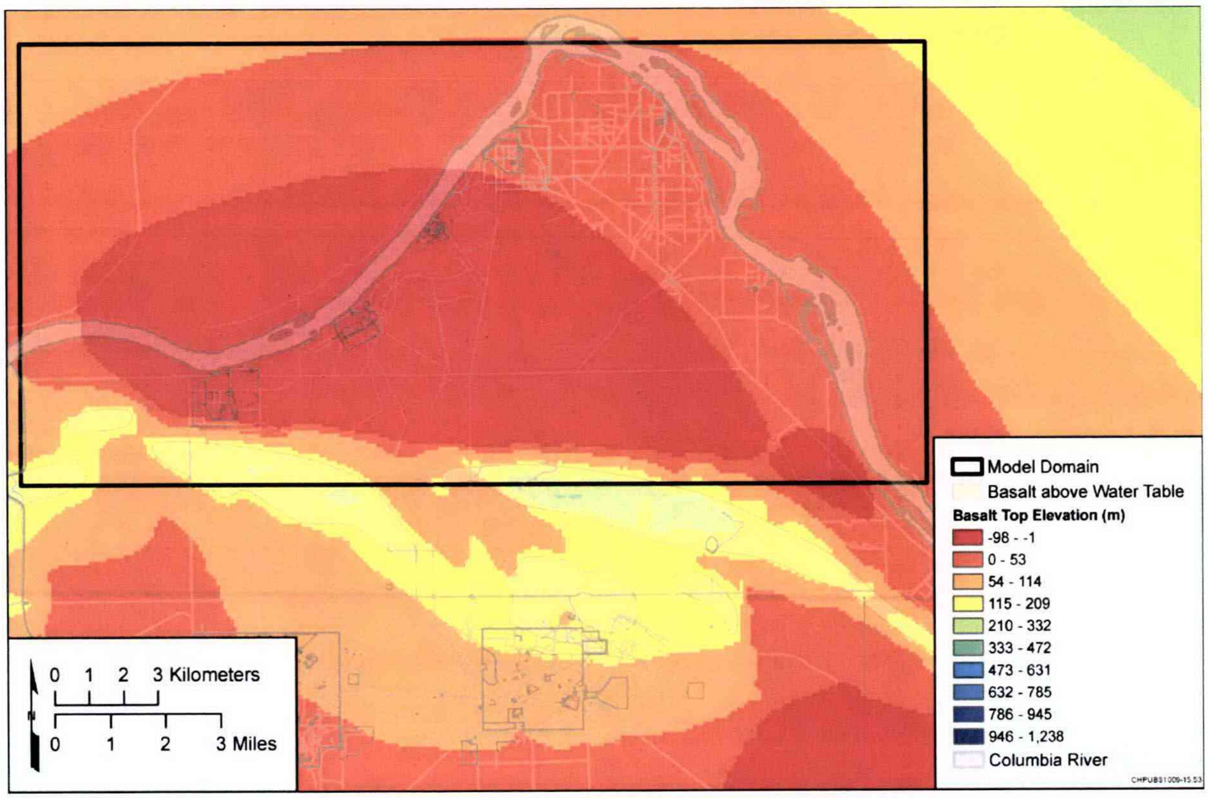


Figure 5-4. Top of Basalt Elevation Dataset.

5.4.2.2 Development of Top of RUM Surface

The RUM elevation surface (representing the top of the RUM) was based on information from the following sources:

- Table 3-1 and digitized elevation contours for 100-HR-3, as presented in *100-HR-3 Remedial Process Optimization Model Data Package* (SGW-40781, Rev. 1)
- Table 3-2 and Digitized elevation contours for 100-KR-4, as presented in *100-KR-4 Remedial Process Optimization Model Data Package* (SGW-41213)
- Table 5-1 and Digitized elevation contours for 100-BC-5, as presented in *100-BC-5 Remedial Process Optimization Model Data Package* (SGW-44022)
- Table 5-1 and Digitized elevation contours for 100-FR-3, as presented in *100-FR-3 Remedial Process Optimization Model Data Package* (SGW-47040)
- Point-data for the RUM top elevation outside the areas outlined in the data packages, in electronic form and hardcopy, as described in *Groundwater Data Package for Hanford Assessments* (PNNL-14753).

Additional available information, including well logs from several wells within the 100 Areas, was not considered in this analysis because it refers to wells drilled more than three decades ago, and the absence of detailed documentation of the geologic description of the sediments prevents a reliable geologic interpretation. The locations of available RUM elevation data are shown in Figure 5-5. A linear variogram was fit to the data which were then interpolated using Kriging on a rectangular mesh of 15m x 15m cells. The interpolated surface (filename "RUMTOP_January2011_LinearVario_NoSearch.grd") was then interpolated using the nearest neighbor method, to the 100 AGWM grid. The resulting surface was exported to a MODFLOW array format as this could be easily processed with available data processing utilities. The mapped RUM Surface is shown in Figure 5-6.

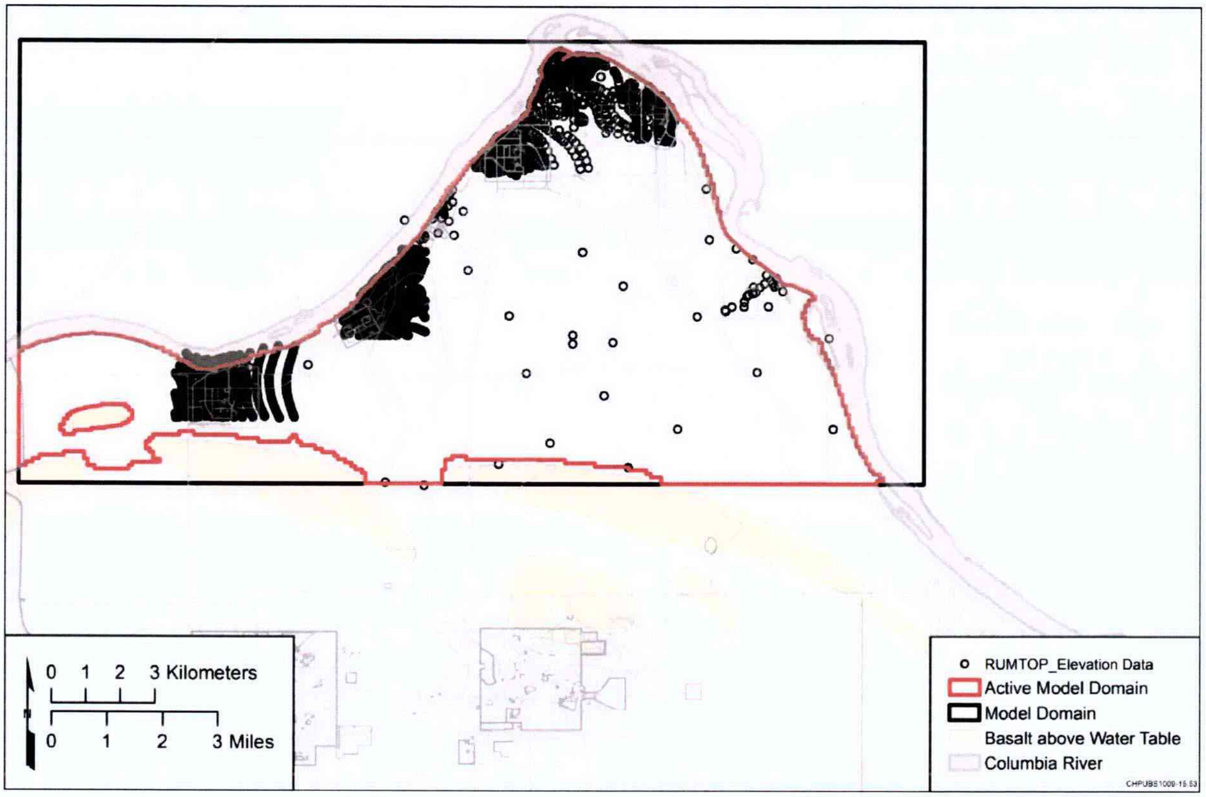


Figure 5-5. Top of RUM Elevation Dataset.

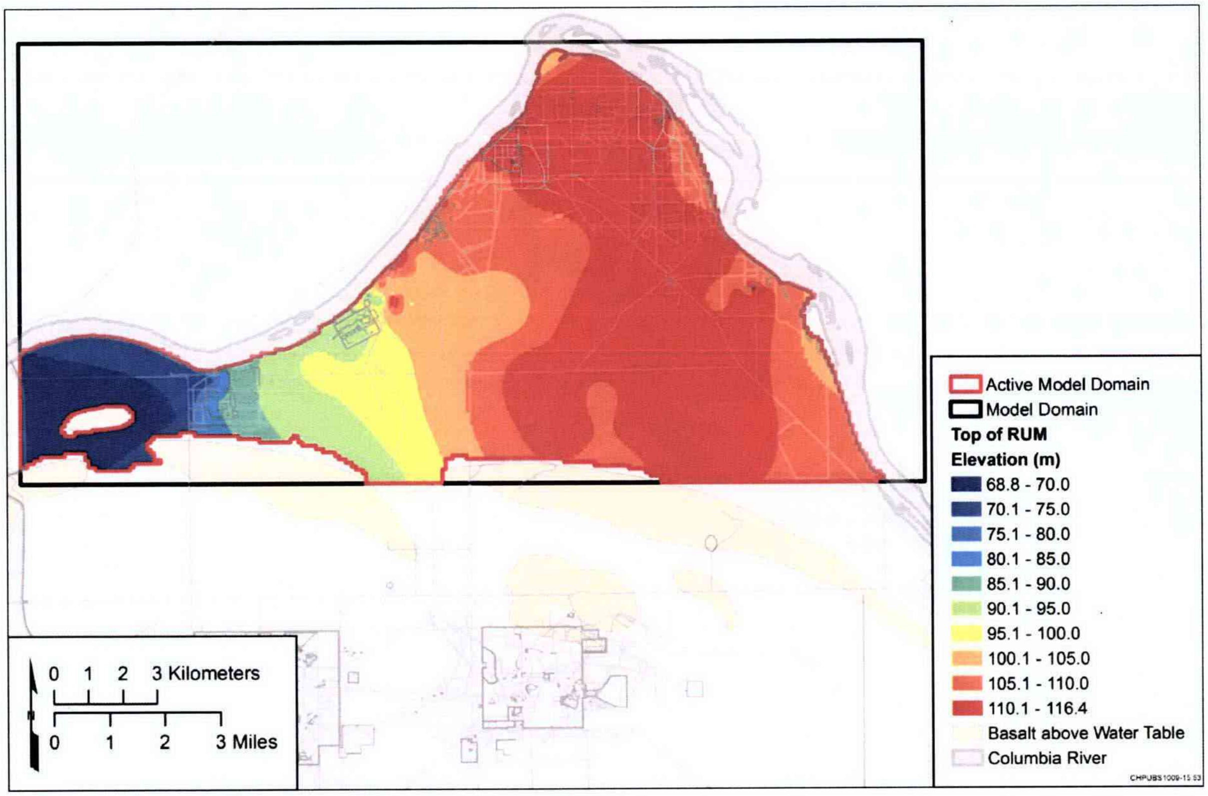


Figure 5-6. Mapped Top of RUM Elevations.

5.4.2.3 Development of Top of Ringold E Surface

The Hanford-Ringold E contact elevation surface was based on information from the following sources:

- Table 3-1 and digitized elevation contours for 100-HR-3, as presented in *100-HR-3 Remedial Process Optimization Model Data Package* (SGW-40781, Rev. 1)
- Table 3-2 and Digitized elevation contours for 100-KR-4, as presented in *100-KR-4 Remedial Process Optimization Model Data Package* (SGW-41213)
- Table 5-1 and Digitized elevation contours for 100-BC-5, as presented in *100-BC-5 Remedial Process Optimization Model Data Package* (SGW-44022)

The location and distribution of the compiled dataset are shown in Figure 5-7. An exponential variogram (defined by a range of 1500, sill 45, nugget 0 and anisotropy 1) was fit to the data. Based on this variogram, the dataset was interpolated on a rectangular mesh with 15m x 15m cells. The interpolated surface (filename "Useme_hrcontact_v8_eXPONENTIALVario_Nosearch.grd") was then interpolated using the nearest neighbor method, to the 100 AGWM grid. In areas where the Ringold E is not present (east of 100-D), the contact elevation was artificially set to be slightly (0.3m) above the RUM surface. The mapped contact Surface is shown in Figure 5-8.

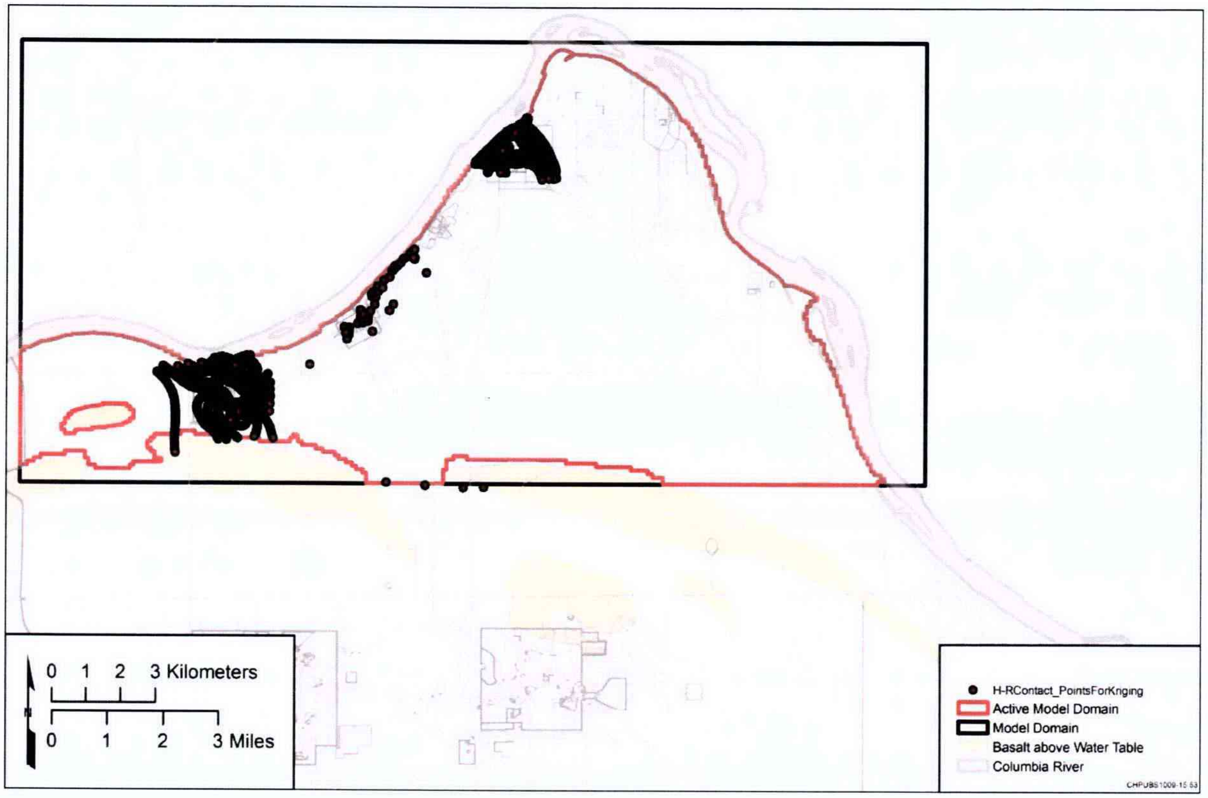


Figure 5-7. Top of Ringold E Elevation Dataset.

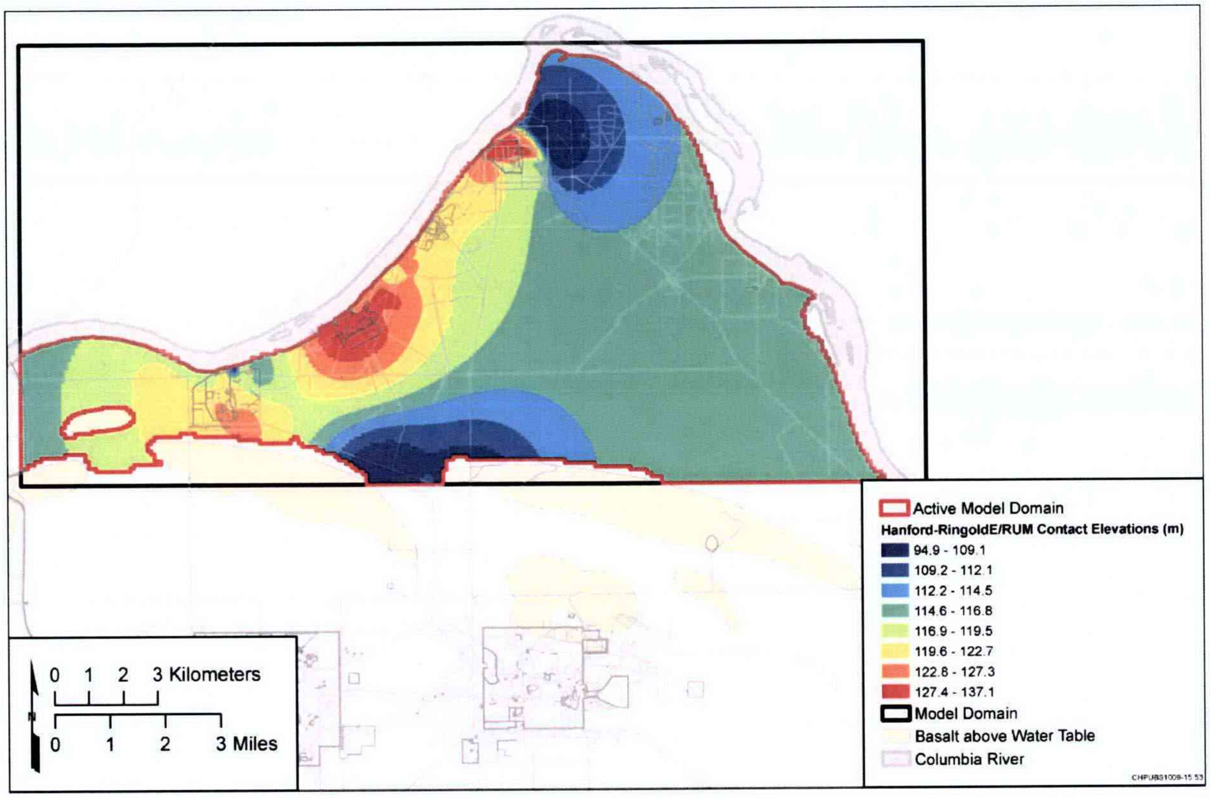


Figure 5-8. Mapped Ringold E Elevations.

5.4.2.4 Model Layer Elevations

The development of the model layer bottom elevation distribution is based on the mapped elevations for the Hanford-Ringold E contact, and the bottom of the Hanford/RingoldE formations which corresponds with the top of the RUM or the top of the basalt.

Bottom of Layer 4: The bottom elevation distribution of Layer 4 – which represents the model bottom elevation - is developed based on a composite surface consisting of the top of RUM across most of the model domain and the top of the basalt where the RUM is not present. To develop that surface, the basalt elevation at each model cell is compared against the RUM elevation at the same location: the higher of the two elevations is selected as the bottom elevation for that cell. The resulting model bottom elevation distribution is shown in Figure 5-9.

Bottom of Layer 1: A systematic procedure was developed to calculate the bottom elevation distributions for Layer 1. At each model cell, the Hanford-Ringold E contact surface is compared against Layer 4 bottom elevation. If the contact surface elevation is found to be below Layer 4, it is artificially adjusted to be 0.3m above Layer 4. Also, in areas where the Ringold E Formation is not present, the contact elevation is set to be 0.3m above Layer 4. Since Layer 1 always represents the Hanford formation, the bottom elevation distribution for Layer 1 is represented by this adjusted contact surface. This surface is shown in Figure 5-10.

Bottom of Layers 2 and 3: The bottom elevation distribution for Layers 2 and 3 are calculated such that – to the extent possible – model Layers 2, 3 and 4 have the same thickness at any model row-column (I, J) location. Due to the thinness of the saturated aquifer in areas east of 100-D where Ringold E is not present, Layers 2, 3 and 4 have a minimum thickness of 0.1 m and each layer represents the Hanford formation. Everywhere else the saturated thickness of the aquifer is considerably greater, so that the thickness of Layers 2, 3 and 4 are the same for each model row-column (I,J) location and vary depending on the total thickness of the Ringold E Formation at that row-column (I,J) location.

The model top elevation surface is derived from a Land Surface Elevation DEM (Gesch, 2007; Gesch et al., 2002). Calculation of the layer bottom elevations was performed using the utility *CalcLayerBottomElev* that is described in Table 5-1.

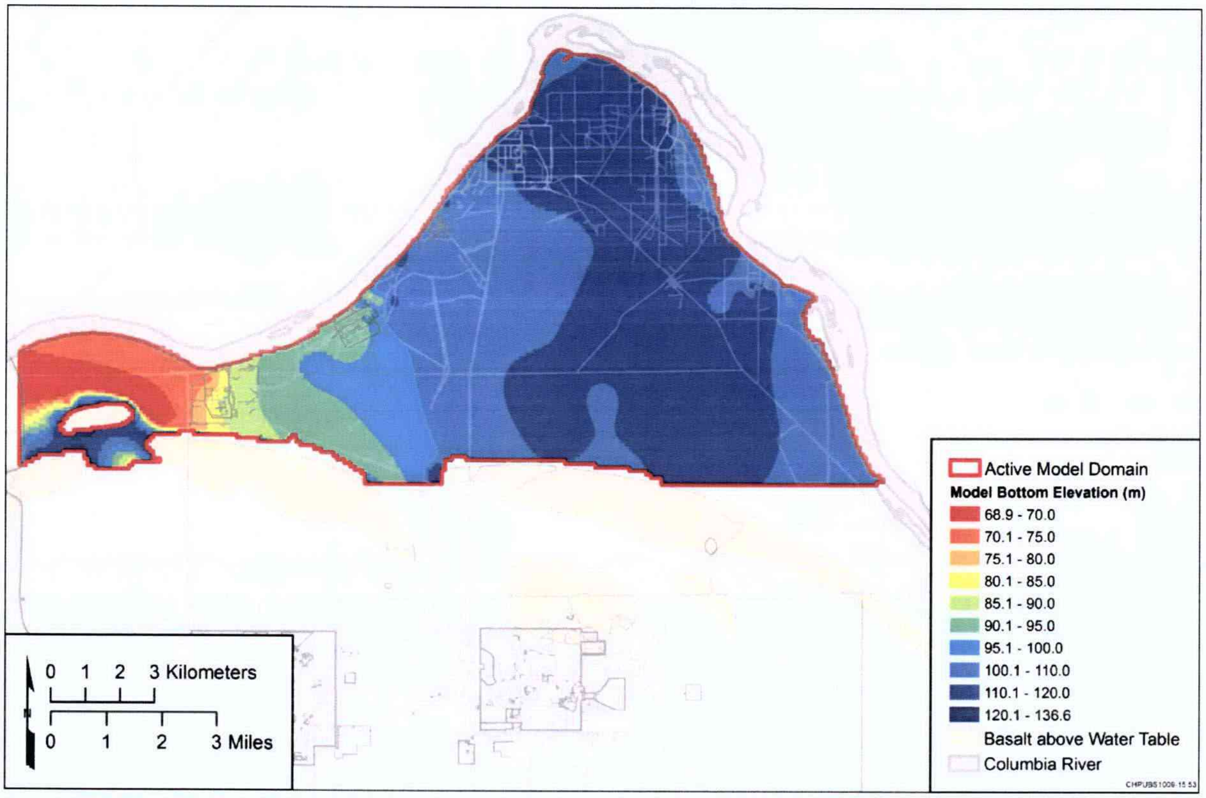


Figure 5-9. Model Layer 4 Bottom Elevation: Top of Basalt/RUM.

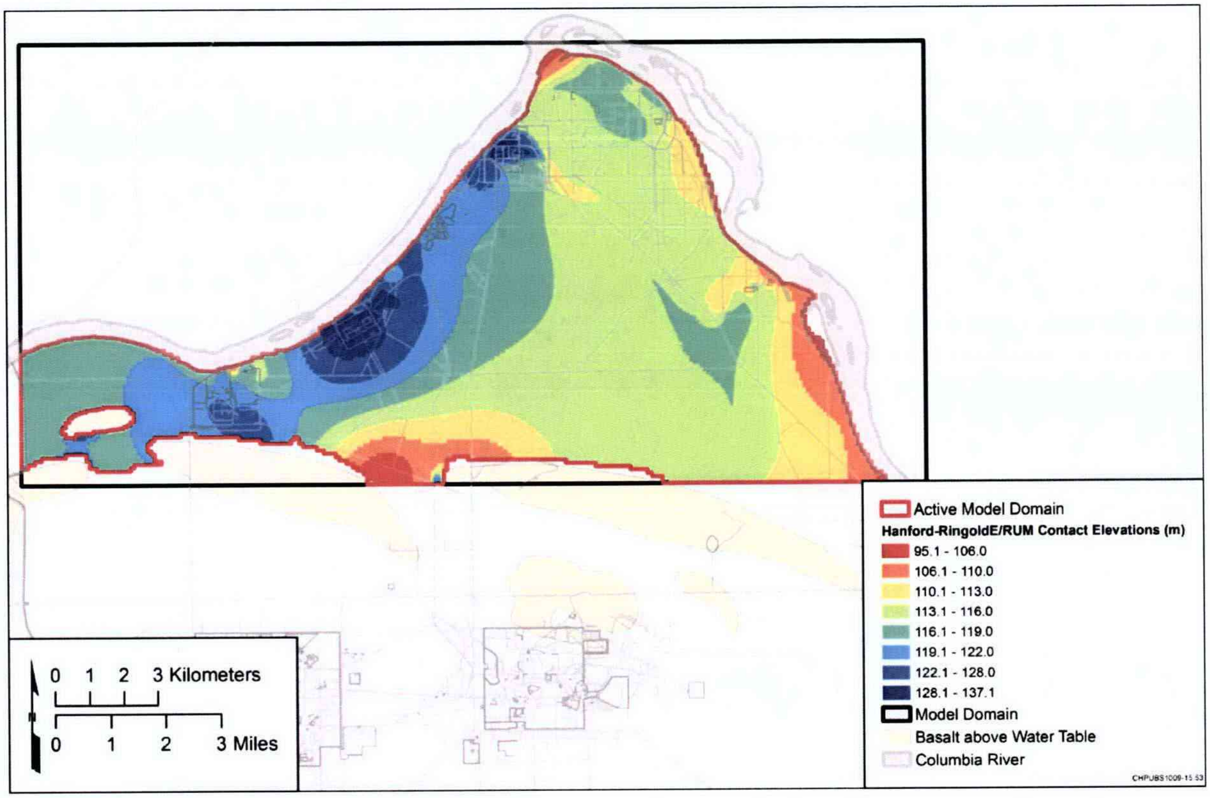


Figure 5-10. Model Layer 1 Bottom Elevation: Hanford-Ringold E or Hanford/RUM/Basalt Contact.

5.5 Simulation Period

The model simulates transient-state (i.e. time-varying) conditions in the aquifer that reflect water level changes due to river-stage variations over time and changing pumping patterns corresponding to P&T operations at each OU. The historic model simulation timeframe spans the period January 2006 through December 2010, consisting of monthly stress periods with three time steps per stress period for a total of 60 stress periods. These stress periods correspond to monthly average river stages, representing the time-varying river stage during that period. The first stress period is simulated as steady-state – i.e., not time-varying, but an effective "average" condition - to produce meaningful initial conditions for the transient stress periods that follow.

5.6 Aquifer Properties

The development of aquifer property distributions for the groundwater model is described in this section. The model parameterization and corresponding refinement of the aquifer property distribution is discussed in Section 7, where the calibration of the model parameters is discussed in detail.

5.6.1 Hydraulic Conductivity

The principal aquifer property that is specified in the 100AGWM is the spatially varying hydraulic conductivity of the saturated aquifer materials. The hydraulic conductivity distribution in the model was developed based on (a) point estimates obtained from slug tests and aquifer pumping tests performed at various well locations plus (b) independent information on aquifer properties from prior modeling efforts and qualitative hydrostratigraphic interpretations - both summarized in the model data packages. The final distribution of hydraulic conductivity was then updated via model calibration (parameter estimation).

The geologic characterization compiled as part of the model data packages depicts the lateral transition from the Ringold Unit E in the west and south of the model domain, to the Hanford formation sands and gravels in the east and north of the model domain. The secondary separation of hydraulic conductivity "zones" within Ringold Unit E reflects broad differences in hydraulic conductivity values between the 100-B/C, 100-K and 100-N Areas and the 100-D Area, as determined from evaluation of the slug and aquifer (pumping) tests. A similar separation appears to occur within the Hanford formation between 100-H and 100-F. This geologic characterization was used to define independent areas for evaluating aquifer properties, on the assumption that the mean and standard deviation should be expected to be relatively constant within each of these areas and to differ between each of the areas. In addition to these broad geologically-defined zones, a sinuous zone of high hydraulic conductivity is defined across all model layers in the vicinity (up gradient) of 100-B/C to represent a highly transmissive channel that runs parallel to the basalt outcrop inland of 100-B/C and appears to connect the Gable Gap with the Columbia River. Evidence for this channel is based upon groundwater level responses in the Gable Gap, and their relation to the Columbia River stage, and optical remote sensing (Light Detection And Ranging or LIDAR) data that together support the presence of an ancestral channel abutting the basalt outcrop.

The estimates of hydraulic conductivity compiled as part of the model data packages were tabulated and assigned to their corresponding aquifer unit. When multiple hydraulic conductivity estimates were available for the same location, the average value of those estimates was used. A complete list of the hydraulic conductivity data used for the development of the hydraulic conductivity distribution in the model is included in Tables 5-2 and 5-3 for the Hanford formation and Ringold Unit E Formation, respectively.

Table 5-2. Hydraulic Conductivity Values for the Hanford formation.

Well	Easting (m)	Northing (m)	Value
699-91-46	575911.00	151156.60	240.9
699-93-48	575094.13	151795.30	18.3
699-96-43	576761.45	152605.31	15.2
199-H3-2B	577628.27	152757.16	30.5
199-H4-11	578141.91	152728.43	19.4
199-H4-12A	578009.15	152912.73	71.1
199-H4-12B	578004.39	152918.47	15.2
199-H4-13	578219.30	152595.27	128.1
199-H4-14	577803.75	152752.36	76.2
199-H4-15A	577904.31	153053.42	53.2
199-H4-15B	577899.60	153059.55	140.2
199-H4-16	577981.91	152591.57	67.1
199-H4-18	578018.29	152756.48	24.4
199-H4-3	577940.49	152858.54	52.0

Table 5-2. Hydraulic Conductivity Values for the Hanford formation.

Well	Easting (m)	Northing (m)	Value
199-H4-45	578156.39	152433.39	30.5
199-H4-46	577883.86	152439.87	36.6
199-H4-47	577891.18	152553.30	27.4
199-H4-48	577792.66	152620.21	24.4
199-H4-49	577713.83	152445.15	27.4
199-H4-7	577804.13	152890.85	21.3
199-H5-1	577650.08	152257.72	33.5
199-H6-1	578236.56	152247.63	21.3
199-F1-2	580011.04	148805.30	36.6
199-F5-42	581285.48	147834.82	24.4
199-F5-43A	581183.87	147948.07	38.1
199-F5-44	581060.85	148043.20	16.8
199-F5-45	580706.88	147683.92	9.1
199-F5-46	580841.34	147781.51	68.6
199-F5-47	580495.51	147508.45	30.5
199-F5-48	580517.58	147690.10	19.8
199-F6-1	581375.87	147564.51	21.3
199-F7-3	579884.71	147112.53	42.7
199-F8-3	580253.99	147253.37	62.5
199-F8-4	580958.51	147123.53	10.7
199-F7-1	579687.20	147022.40	225.0
699-71-30	580603.30	145226.90	33.0

Table 5-3. Hydraulic Conductivity Values for the Ringold Unit E Formation.

Well	Easting (m)	Northing (m)	Value (m/d)
199-K-33	568573.65	146713.25	5.8
199-K-107A	568579.94	146468.81	1.6
199-K-34	568605.78	146501.94	20.7
199-K-108A	568687.20	146396.14	1.0
199-K-106A	568697.40	146502.39	2.7
199-K-35	568832.33	146110.68	37.8

Table 5-3. Hydraulic Conductivity Values for the Ringold Unit E Formation.

Well	Easting (m)	Northing (m)	Value (m/d)
199-K-10	568912.76	146628.10	16.1
199-K-32A	569024.15	147006.68	24.4
199-K-110A	569230.01	146677.91	5.4
199-K-111A	569308.17	146968.88	8.1
199-K-18	569353.69	147400.81	2.8
199-K-36	569373.80	146390.73	26.5
199-K-19	569458.52	147386.64	1.8
199-K-20	569520.52	147687.24	33.8
199-K-21	569769.90	147932.06	5.0
199-K-22	570023.70	148097.38	0.9
199-K-37	570216.20	148226.54	44.2
199-N-119	571364.50	149968.34	5.5
199-N-120	571366.18	149970.76	5.9
199-N-121	571368.29	149973.29	3.7
199-D4-1	572752.85	151558.89	23.2
199-D4-4	572754.61	151571.61	32.1
199-D4-9	572758.20	151543.32	16.3
199-D4-7	572760.87	151551.25	16.7
199-D4-8	572763.30	151552.65	10.9
199-D4-3	572766.08	151546.12	18.0
199-D4-2	572768.37	151543.96	17.7
199-D4-11	572768.94	151554.14	12.3
199-D4-12	572771.58	151562.08	22.4
199-D2-6	573000.21	151119.86	12.2
199-D5-19	573239.97	152030.15	12.2
199-D5-97	573250.11	151302.47	48.2
199-D5-104	573265.48	151422.43	72.0
199-D5-122	573302.28	151346.10	50.9
199-D5-119	573306.49	151415.12	47.6
199-D2-11	573328.16	151120.73	62.5
199-D5-99	573349.61	151402.01	28.1

Table 5-3. Hydraulic Conductivity Values for the Ringold Unit E Formation.

Well	Easting (m)	Northing (m)	Value (m/d)
199-D5-98	573369.56	151272.44	51.5
199-D5-102	573428.15	151340.23	72.3
199-D5-121	573429.90	151399.28	8.5
199-D5-103	573505.87	151460.87	30.8
199-D8-55	573620.95	152364.35	6.1
199-D5-16	573730.52	151322.83	3.1
199-D5-14	573738.61	151673.75	9.1
199-D5-15	573789.63	151787.99	9.1
199-D5-20	573849.12	151243.19	12.2
199-D5-18	573861.70	151325.18	18.3
199-D5-17	573917.45	151652.51	3.1
199-D8-3	573942.43	152347.93	11.0
199-D8-53	573889.86	152452.26	161.5
199-K-110A	568778.17	146224.38	9.0

The measured hydraulic conductivity dataset was supplemented by additional point locations for specification (and estimation, through calibration) of hydraulic conductivity values in the form of pilot points distributed across each zone: doing so provides flexibility in the assignment and/or estimation of the hydraulic conductivity distribution across the OUs. A description of the use of the pilot point method for the calibration of groundwater models is provided by the article "*Ground Water Model Calibration Using Pilot Points and Regularization*" (Doherty, 2003).

Pilot point locations were selected to ensure sufficient coverage of each OU, especially in areas where there is a limited availability of measured hydraulic conductivity values but where observations of groundwater level are present for inclusion in the model calibration. The locations of measured hydraulic conductivity values as listed in the table above, and of pilot points used for the Hanford and Ringold Unit E formation, are shown in Figures 5-11 and 5-12. It should be noted that pilot points across the Horn were assigned a value equal to the mean hydraulic conductivity of the corresponding zone, as very limited water level data are available in that area for use in calibration to infer any variability (heterogeneity). Ongoing characterization efforts combined with data from newly installed RPO extraction wells in that area will provide necessary information for improved model calibration. Also, recently completed slug tests in 100-K, 100-B/C, 100-F, 100-D and 100-H will provide additional hydraulic conductivity estimates to be added to the calibration dataset in the next update of the 100AGWM.

To populate the 100AGWM model cells with the necessary values of hydraulic conductivity, interpolation from these point data to the model cells was completed. Simple kriging using FIELDGEN, a PEST application, was used to interpolate the measured and pilot-point estimated values within each area independently (Doherty, 2011; Khambamhettu et al, 2011). A spherical variogram was defined for each of these three areas. The zone-specific mean value, and the three variables of the variogram (Nugget (near-field [semi-]variance), Sill (total [semi-]variance), and Range (correlation length)) for each zone, as well as the pilot-point values of hydraulic conductivity were estimated through the calibration process. The calibration (described in Section 6) was undertaken using a combination of manual (trial and error) and automated (optimization) techniques.

Vertical hydraulic conductivity was defined on the basis of horizontal hydraulic conductivity by specifying the vertical anisotropy. A value of 0.1 was assumed for vertical anisotropy, defined as the ratio of horizontal to vertical hydraulic conductivity. Aquifer test data suggest that vertical anisotropy is in the range of 0.01 to 0.1 (PNNL-10886, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*). Due to the large horizontal scale and relatively small vertical extent of the simulated HSUs the model calibration is relatively insensitive to the value of vertical anisotropy, although local-scale predictions of contaminant transport may be more sensitive to this parameter.

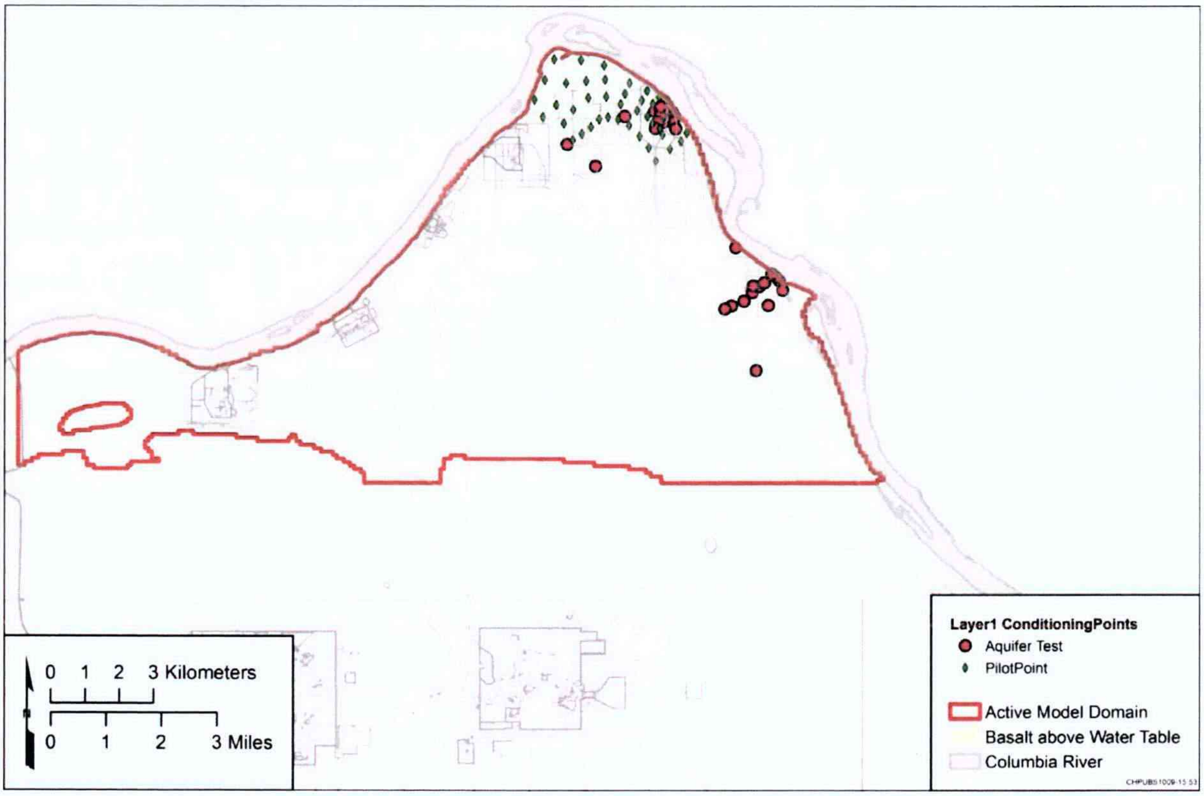


Figure 5-11. Location of Measured Hydraulic Conductivity Data and of Pilot Points: Hanford formation.

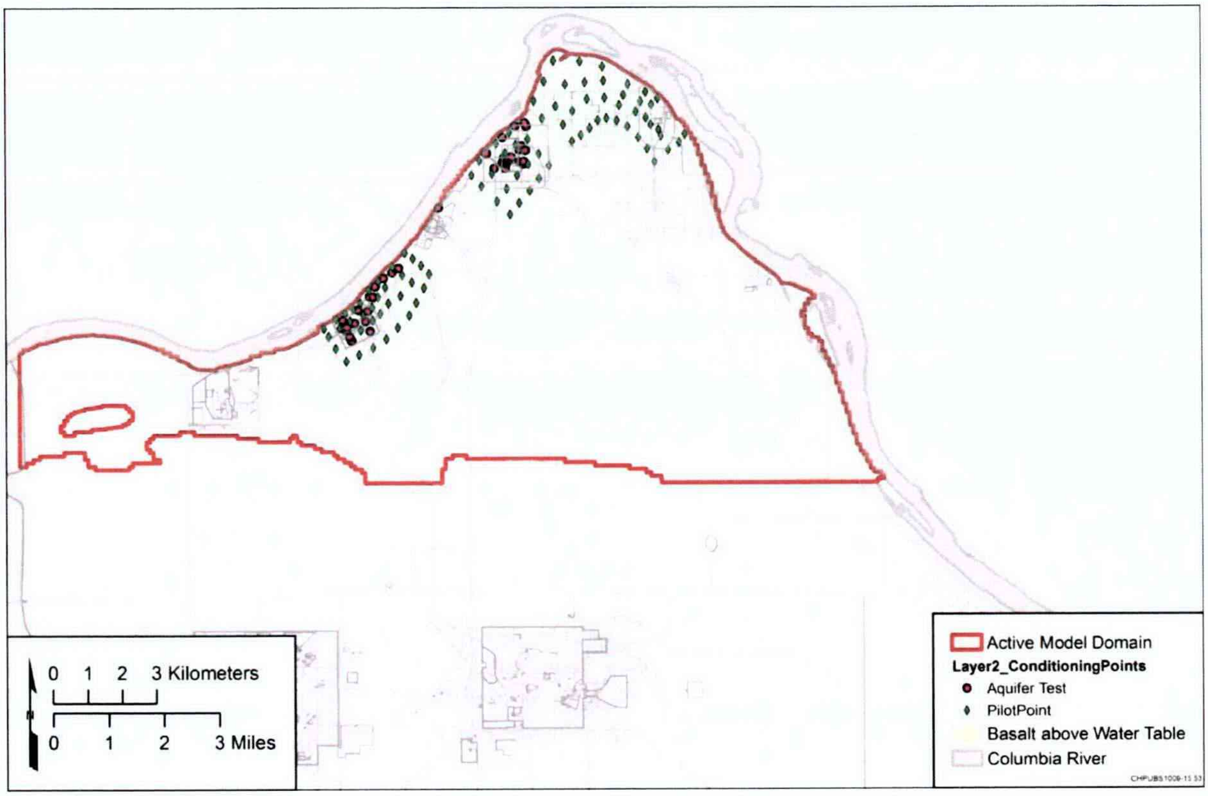


Figure 5-12. Location of Measured Hydraulic Conductivity Data and Pilot Points: Ringold Unit E Formation.

5.6.2 Porosity and Storage

Effective porosity and specific yield values for the entire aquifer were determined from the model calibration and are equal to 0.18 and 0.10, respectively. Both values are within the range of values documented in previous investigations for the Hanford Site (PNL-10886, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report;* PNL-14753, *Groundwater Data Package for Hanford Assessments*). The specific yield value of 0.10 results in a satisfactory simulated groundwater response to changes in the Columbia River stage but is lower than the expected field value of specific yield: this results from the preponderance of fairly short oscillations in the Columbia River stage which duration does not illicit the full value of the specific yield. A similar phenomenon has been noted in aquifer tests conducted in the Central Plateau (Spane, 2010) which suggested that many weeks of drawdown (i.e., sustained head change) may be required before the bulk of the water table drainage occurs. Although use of 0.10 for specific yield in the historic model results in an improved calibration versus the use of higher values, the use of this value in predictive simulations may result in more rapid simulated stabilization of the aquifer in response to groundwater extraction than will be measured in the field.

A specific storage value of 5×10^{-6} day^{-1} was assumed for the entire model domain. This value lies within the range of values in the literature for similar geologic data and it is also within the range of values documented in previous investigations for the Hanford Site (PNNL-10886, *Development of a Three-Dimensional Ground-Water Model of the Hanford Site Unconfined Aquifer System: FY 1995 Status Report*).

5.7 Boundary Conditions

The MODFLOW model domain comprises active cells where the flow of groundwater is simulated and inactive cells where the flow of groundwater is not simulated. In general, the inactive cells are located beyond the shores of the Columbia River that form the lateral extents of the model to the northwest and northeast, and also in the area of Gable Mountain and Gable Butte to the south.

The MODFLOW simulation code comprises a main program that provides the basic requirements for simulating groundwater flow, as well as a series of packages that provide the capability to simulate particular features of the groundwater system. The 100AGWM MODFLOW model uses packages that simulate:

- Flow of water to and from major surface water bodies (river package [RIV]);
- Lateral flow into and out of the model domain based on information about the aquifer transmissivity and hydraulic gradient (general head boundary package [GHB]).
- Lateral flow into and out of the model domain based on a prescribed hydraulic head at particular cells (constant head boundary package [CHD]);
- Areal recharge (recharge package [RCH]);
- Flow of water to and from wells (multi-node well package [MNW2]);

Figure 5-13 illustrates the distribution of active and inactive model cells, and the location of lateral boundaries specified for the 100AGWM MODFLOW model.

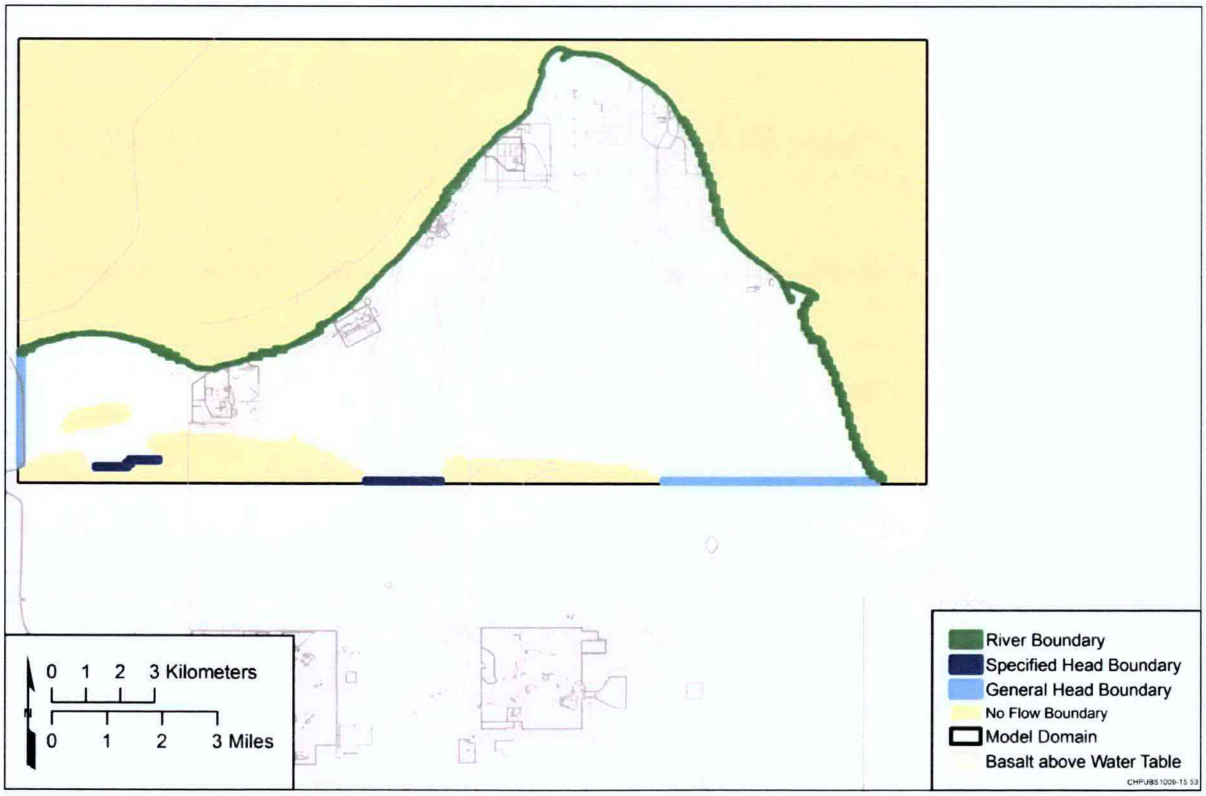


Figure 5-13. Location of Active and Inactive Model Cells, and Lateral Boundary Conditions.

5.7.1 River Boundary

Along the north and northeast boundaries of the model the river package (RIV) was used to represent the flow of water to and from the Columbia River. The location of the river boundary in the 100AGWM is shown in Figure 4-10.

River stage data from six gauges located in the vicinity of each OU (100-B/C, 100-K, 100-N, 100-D, 100-H and 100-F) as well as the USGS gauge 12472800 located below Priest Rapids Dam were processed and summarized for the period January 2006 through December 2010. The monthly average values were compiled to provide the necessary dataset for the calculation of river stage for each river boundary cell of the model for each simulated stress period. Data gaps were identified for 100-K and 100-F gages and a systematic procedure was followed to substitute best-estimate values in those gaps so that monthly average values could be calculated for each gauge:

- River stage data at the 100-F gauge were compared with data from the 100-H gauge located further upstream, and an average ratio of 100-F gauge versus 100-H gauge river stage was developed for each month.
  - Missing 100-F gauge data points were then calculated by multiplying the corresponding 100-H gauge stage by the average 100-F/H ratio for that particular month.
- Similarly, river stage data at the 100-K gauge were compared with the data from the 100-B/C gauge located further upstream, and an average ratio of 100-K gauge versus 100-B/C gauge river stage was developed for each month.
  - Missing 100-K gauge data points were then calculated by multiplying the corresponding 100-B/C gauge stage by the average 100-K/B ratio for that particular month.

After all data gaps were eliminated, the utility *4_RiverPackage.exe* was used to generate the monthly average river stage for each grid cell representing the river boundary package. A separate utility, *rivrewrite.exe*, was used to determine the appropriate model layer to apply the river boundary, such that the only model grid cells with bottom elevation lower than the river stage are designated river boundary cells. Finally, riverbed conductance values were determined through the calibration process, separately for the stretches of the Columbia River within each area in order to reflect variability in geologic conditions in each one of those areas.

5.7.2 General Head Boundary

The general head boundary package was used to represent the flow into and out of the model domain along (a) the southeast model boundary between the Gable Mountain and the Columbia River; and (b) the western boundary of the model.

The hydraulic head specified for this general head boundary package was calculated on the basis of a map of site-wide groundwater elevations representing typical groundwater-level conditions for the period 2006-2008, together with data identifying river stage variation for the period 2006-2010. The following procedure was developed to calculate the boundary water levels for the general head boundary package for each stress period:

- Site-wide groundwater level data for the month of March for each of the years 2006-2008 were compiled, and a water level surface was calculated based on the average value at each monitoring location (DOE/RL-2008-66, *Hanford Site Groundwater Monitoring for Fiscal Year 2008*).

- The most inland cell along each general head boundary was assigned a water level value based on interpolation from the water level surface previously calculated.
- The cell at the opposite end of the general head boundary was assigned a water level value corresponding to the river stage elevation as included in the river package for that particular period.
- The water level value for the remaining general head boundary cells was obtained through interpolation between the two edge-cell values.
- The procedure was repeated for each stress period.

5.7.3 Constant Head Boundary

The constant head boundary package was used to represent the time-varying hydraulic head distribution along model cells representing (a) The Western Gap and (b) the Gable Gap, between the Gable Butte and the Gable Mountain. The prescribed hydraulic head at those boundary cells is consistent with hydraulic heads calculated by the Central Plateau model at the same locations, which enables the 100AGWM to approximately simulate the flow of water in and out of the model domain at those locations.

5.7.4 Areal Recharge

Areal recharge from precipitation was discussed in detail in Section 3.4.1. Based on this information, PNNL developed a recharge distribution which was included in the Groundwater Data Package for Hanford Assessments (PNNL-14753, *Groundwater Data Package for Hanford Assessments*).

An electronic version of the recharge package developed in the PNNL report was obtained, and the data were spatially distributed to the model grid cells. Based on the results of the model calibration, the recharge value specified in the 100AGWM domain was then uniformly scaled to provide improved fit to measured groundwater elevations. This resulted in a typical value for groundwater recharge equal to 12 mm/yr throughout the model domain.

5.7.5 Well Pumping

Extraction and injection rates for the 100 Area P&T wells for the period January 2006 through December 2010 were obtained from CHPRC in the form of Microsoft Excel worksheets. The following data files were obtained:

- DR-5 Extraction Pumping Rates.xlsx
- HR-3 Extraction Pumping Rates.xlsx
- HR-3 Injections Pumping Rates.xlsx
- KW Extraction Pumping Rates.xlsx
- KW Injection Pumping Rates.xlsx
- Rest of K extraction pump rates.xlsx
- Rest of K injection pump rates.xlsx

During the period 2006-2010 the following treatment systems (and associated extraction/injection wells) were operational or became operational:

- KW, KR and KX in 100-K.

- DR-5 in 100-D.
- HR-3 in 100-H.

Monthly average pumping rates were calculated for each well from hourly data. No pumping was assumed for missing entries. Well 199-D5-42, the only injection well connected to the DR-5 treatment system, did not have measured injection rates and therefore the corresponding values were calculated by adding the extraction rates of the wells that are connected to the same treatment system, i.e. 199-D5-20, 199-D5-32, 199-D5-39, and 199-D5-92.

Reported extraction rates for well 199-K-35 for April, May, and June 2009 were not used because of unresolved anomalies in the reported data. Spatial coordinates and screen elevations of extraction/injection wells were obtained from the HEIS database via CHPRC. Screen top and bottom elevations for wells 199-H4-3, 199-H3-2A, 199-K-174, and 199-K-175 were unavailable at the time of model construction and therefore these wells were assumed to be fully penetrating.

Screen bottom elevations for eight wells were found to fall below the model bottom elevation as calculated based on the procedure described in previous Section 6.2. This could be attributed to the difference between the interpolated elevation of the RUM surface and the actual elevation of the RUM at that location, due to the interpretation of the geologic units in the vicinity of the particular well. To ensure that all extraction/injection wells are included in the model and their operation is reasonably implemented in the simulation, the top and bottom screen elevations were adjusted upwards so that the bottom of screen elevation is the same as the model bottom elevation at the corresponding model cell.

Figures 5-14 to 5-16 illustrate the location of the extraction/injection wells that were or became operational during the period 2006-2010 in 100-K, 100-D and 100-H, respectively.

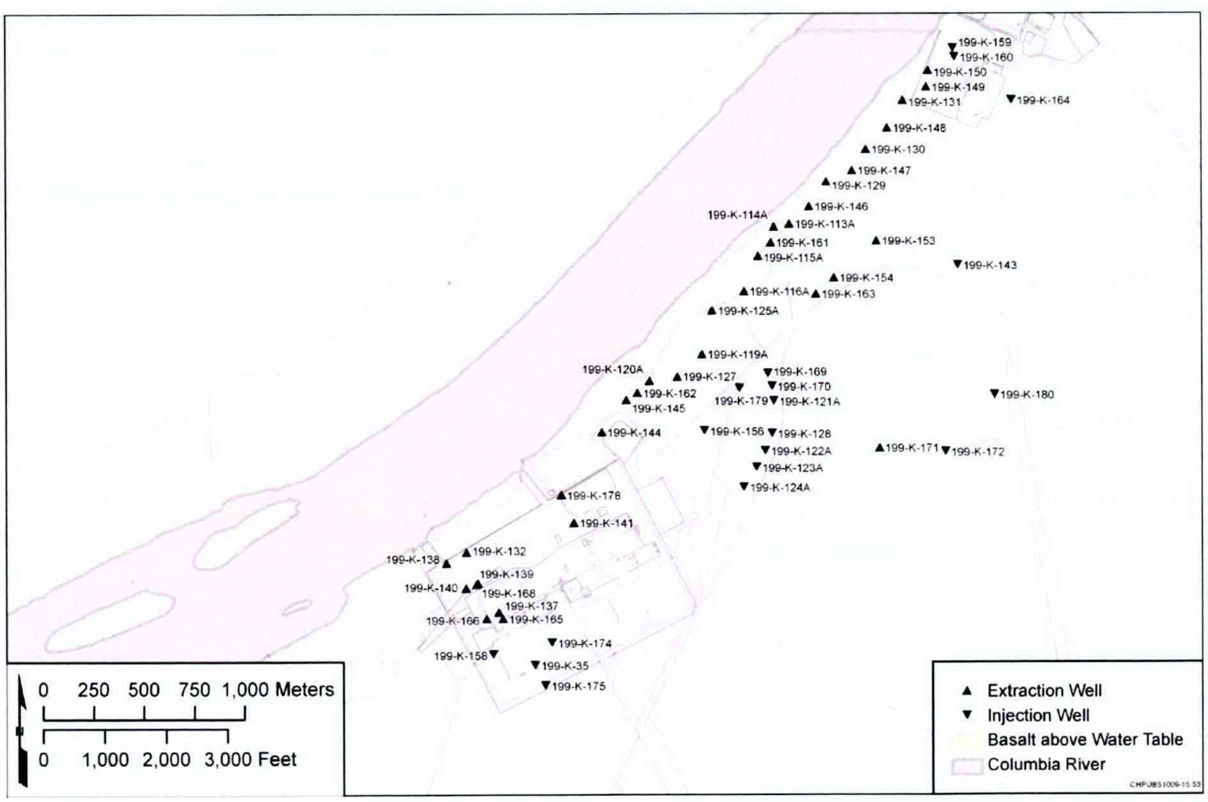


Figure 5-14. Extraction/Injection Wells in 100-K.

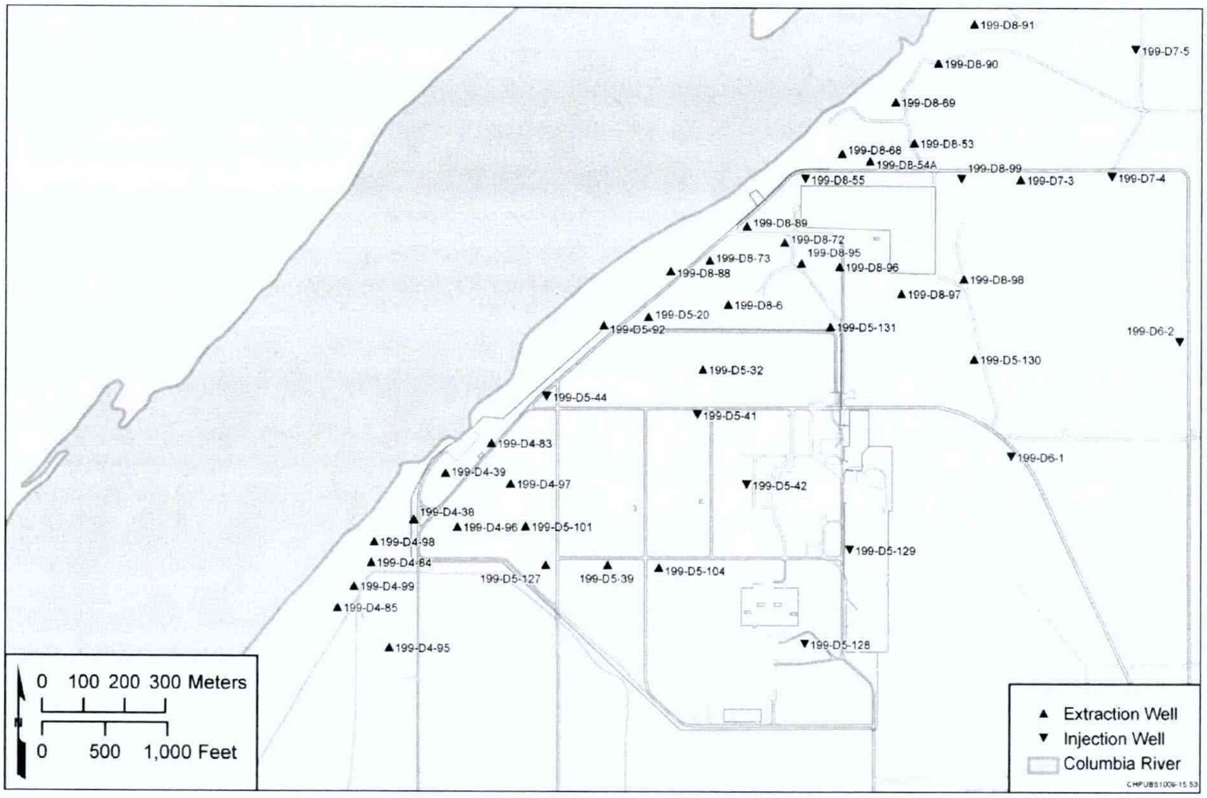


Figure 5-15. Extraction/Injection Wells in 100-D.

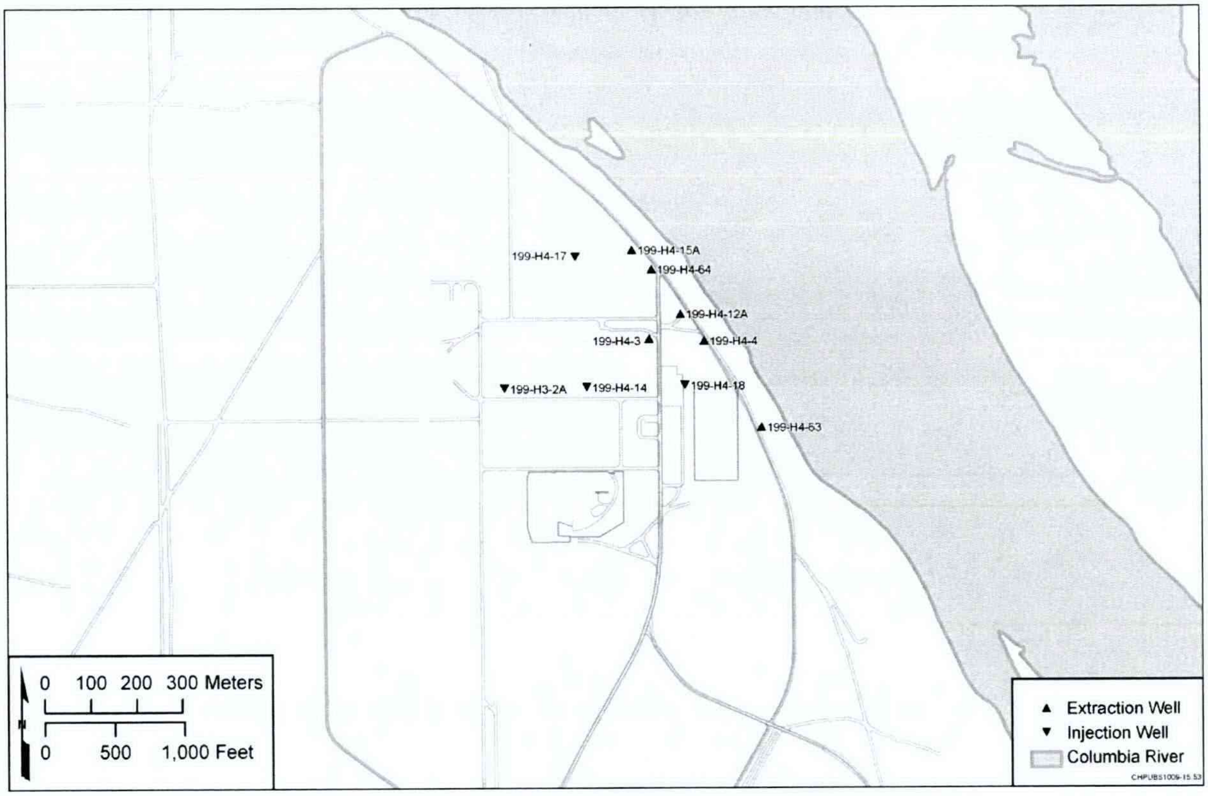


Figure 5-16. Extraction/Injection Wells in 100-H.

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6 Flow Model Calibration

The groundwater flow component of the 100AGWM was calibrated to groundwater level data, using as a starting-point the information on likely parameter values included in the model data packages.

Values for some of the boundary conditions and aquifer parameters that are described above were estimated through a manual (trial-and-error) and automated calibration process. The model calibration process was facilitated, in part, by the use of the automated calibration tool PEST (Doherty, 2011) together with post-processing programs that were developed to calculate simulated groundwater-level responses to stresses such as pumping and river stage changes. Due to the relatively long historic (calibration period) model simulation run times, model calibration was expedited by a combined qualitative and quantitative (automated) adjustment of parameter values. The model was calibrated to data from throughout the period January 2006 to June 2009. The model calibration process focused on:

- Simulating the transient response of groundwater levels to changing stresses and how these compare to measured responses at monitoring locations possessing continuous groundwater level records were available at the 100-K, 100-D, and 100-H Areas. The simulated aquifer response was also evaluated in 100-B/C and 100-F where only manual water level measurements are available for the calibration period.
- Simulating the direction and magnitude of hydraulic gradients in the vicinity of each reactor area and across the 100 Areas in general. This was accomplished by:
    - Directly comparing simulated and measured hydraulic gradients calculated from model outputs and from measured water levels using the three-point gradient technique in proximity to the reactor areas (Silliman and Frost, 1998).
    - Comparing maps of groundwater-level contours calculated by the model to contours included in published reports to ensure that the simulated gradients are in broad agreement with independently interpreted values (DOE/RL-2008-66, *Hanford Site Groundwater Monitoring for Fiscal Year 2008*).

6.1 Compilation and Disposition of Hydraulic Head Data

Transducer data recording hourly groundwater levels at monitoring wells in the 100-H/D and 100-K Areas, and river stage elevations at the 100-B/C, 100-K, 100-N, 100-D, 100-H, and 100-F river gauges were compiled for the period January 2006 through June 2009. In addition to these automated data, manually-recorded groundwater level measurements at selected monitoring wells were reviewed and compiled to complement the automated water level data. Datasets were obtained from CHPRC in the form of Microsoft Excel worksheets included in the following files:

- B-D Redux 2006-2010.xlsx
- B-D Redux 2006-2010.xlsx
- F-River 2006-2011.xlsx
- H-river CY2006-10.xlsx
- K-River CY08-2010.xlsx
- N-River CY2006-10.xlsx

- NR-2 CY2010 Dataset(1).xlsx
- HR-3 Horn Wells Dataset CY2010.xlsx
- HR-3D CY2010.xlsx.xls
- HR-3H_CY10_Dataset.xlsx
- KR-4 CY2010.xlsx

The entire dataset was reviewed and compiled into a Microsoft Access database: "100AreaWL_2006-2010_forCalibration.accdb". Daily average water elevations at each well were calculated from the hourly measurements and were used for calibration of the flow component of the 100AGWM.

6.2 Review and Disposition of Well Screen Data

Well screen data were obtained from HEIS (DOE/RL-93-24-1, *Hanford Environmental Information System*) through queries used by SSP&A to retrieve this information. These data were reviewed together with corrections and additions provided by CHPRC for some wells.

6.3 Calibration

Model parameters were determined based on manual and automated calibration using the model calibration software package PEST. The calibration methodology relied on the implementation of the hybrid regularized inversion (calibration) technique available through PEST. This technique comprises a combination of the following:

- Parameterizing the aquifer hydraulic conductivity using pilot points as described earlier, distributed throughout the model domain in broad zones that exhibit relatively consistent mean values, but for which there is evidence of variability. The parameterization is accomplished using Fieldgen and the broad zones comprise:
    - 100-H: Hanford formation
    - 100-F: Hanford formation
    - 100-D: Principally, Ringold Unit E
    - 100-K: Principally, Ringold Unit E
    - 100-B/C: Principally, Ringold Unit E
- More simplistic parameterization of aquifer storage properties (specific yield and storativity) using model-wide average values.
- Use of singular value decomposition (SVD) and of the hybrid Tikonov-SVD ("super parameter) technique, together with trial-and-error calibration, with parameter value adjustments based on qualitative evaluation of the estimated aquifer parameter values, prior independent information on these values, and the correspondence between simulated and measured groundwater levels and hydraulic gradients.

As a result of this approach to calibration, estimated parameters included:

- The mean hydraulic conductivity for each defined zone, as described in Section 6.4.1;

- Variogram parameters (nugget, sill, and range) to define the hydraulic conductivity distribution in each area; and
- Spatially varying hydraulic conductance for the river boundary and the general head boundaries.

The model was calibrated to water level data from 94 monitoring wells for the period January 2006 to June 2009. Maps of the monitoring wells in each OU are shown in Figures 6-1, 6-2, 6-3, 6-4, and 6-5. A total of 10,441 water level measurements were tabulated for the calibration process.

To mitigate the impact of initial conditions on the calibration process, residuals (differences between the simulated and measured heads and gradients) calculated during the first 90 days of 2006 were excluded from the calibration by assigning those comparisons (residuals) a zero weight. This resulted in 576 measurements being excluded, with the remaining 9,865 measurements used as calibration targets and assigned equal weights.

In addition to simulating groundwater level responses, the model was calibrated to match the observed magnitudes and directions of hydraulic gradients directly. Doing so is considered particularly important the both the model calibration process, and to the use of the model for groundwater remedy design, since the direction and magnitude of hydraulic gradients is a first-order determinant in the direction and rates of contamination migration. To calculate observed gradients, triangular elements were developed based on the location of monitoring wells in each OU. For each of these triangular elements, monthly average groundwater levels were used to calculate the direction and magnitude of the hydraulic gradient each month. The post-processing utilities *headtargs* and *calcgradients* were used to calculated both the observed, and the corresponding simulated, hydraulic gradients. A total of 70 triangular elements was used to assess the model performance in this regard. The triangular elements for each OU that were considered in the 100AGWM calibration process are shown in Figures 7-6, 6-7, 6-8, 6-9 and 6-10.

The simulated outputs were compared to the measured data obtained from each monitoring well, for each time that a measured value is available. These comparisons were compiled into various statistical and graphical forms – including scatter diagrams, time-series plots, and residual statistics - to evaluate the performance of the model and guide adjustments to model parameters. Table 6-1 includes statistical metrics that are routinely used to evaluate model calibration progress. In summary, the Mean Error (ME, equivalent to the average residual) is 0.24 m and the Mean Square Error (MSE, also known as the Variance) is 0.19 m^2. The Root Mean Square Error (RMSE, also known as the Standard Deviation) is 0.44 m. The Coefficient of Determination (R^2) is 0.95 suggesting that measured and calculated water levels are highly correlated. The positive average residual indicates an overall positive bias in the model, i.e. the simulated water levels are lower than the observed water levels. The low RMSE value suggests a reasonable fit between the measured and calculated water levels.

Table 6-1. Calibration Statistics.

Metric	100 Area	100-B/C	100-K	100-D	100-H	100-F
Coefficient of Correlation	0.97	0.84	0.91	0.92	0.88	0.93
R^2	0.95	0.71	0.83	0.85	0.77	0.86
Average Residual (m)	0.24	0.45	0.36	0.25	0.05	0.01
Maximum Residual (m)	11.19	1.52	11.19	1.14	1.36	0.94
Minimum Residual (m)	-1.53	-0.31	-1.53	-0.45	-0.31	-1.19

Table 6-1. Calibration Statistics.

Metric	100 Area	100-B/C	100-K	100-D	100-H	100-F
Sum of Squared Errors (SSE, m^2)	1993.6	69.7	1195.5	582.7	127.9	17.8
Mean Squared Error (MSE, m^2)	0.66	0.77	0.81	0.57	0.50	0.60
Root Mean Squared Error (RMSE, m)	0.44	0.60	0.66	0.33	0.25	0.36
Observed Range (m)	22.35	6.71	17.23	3.27	3.24	8.59
RMSE / Observed Range (%)	1.96	8.96	3.86	10.04	7.77	4.20

The range of the measured water levels is 22.35 meters. The ratio of the RMSE to the range of the measured values is 1.96%: a ratio of less than ten percent is often used as one line of evidence to support a satisfactory calibration. However, in such a dynamic environment as the Hanford River Corridor, visual comparison of simulated and measured data using scatter plots, frequency plots and hydrographs is perhaps the most suitable means for evaluating how well the model reproduces the observed groundwater response.

The correspondence between measured and calculated water levels is illustrated with a scatterplot in Figure 6-11. Area-wise scatter plots are shown in Figure 6-13, Figure 6-16, Figure 6-19, Figure 6-22 and Figure 6-24. A cumulative frequency chart of the residuals is illustrated in Figure 6-12. This chart summarizes the distribution of residuals for the entire model. The residuals are normally distributed about a value of 0.24 m. Similar charts for each OU are shown in Figure 6-15, Figure 6-18, Figure 6-21, Figure 6-24, and Figure 6-27, respectively. Review of these plots indicates that residuals in HR-3-H & FR-3 Areas are normally distributed about a zero mean, while in BC-5, KR-4 and HR-3-D Areas the residuals are distributed around a positive mean suggesting a positive bias, i.e. the model is under-predicting the water levels in those areas. This systematic error (i.e., bias) may be attributable to systematic errors in reported river gauge data in 100-B/C and 100-K, since the river gauges at these locations have occasionally been displaced or disturbed, thereby altering the reference elevation of those gauges. Furthermore, ongoing characterization in the vicinity of 100-B/C and review of available data near Gable Gap suggest that the hydraulic conductivity distribution – in particular, the location and properties of the high-hydraulic conductivity channel - in those areas may not be accurately defined which could impact the accuracy of the simulated response in those areas.

Comparisons of the hydraulic gradient magnitude and direction calculated from measured and simulated water levels for each OU are presented in Figures 6-14, 6-17, 6-20, 6-23, and 6-26. Limited data availability in 100-B/C prevents a rigorous assessment of the model performance based on hydraulic gradients in that OU. In each of the OUs for which there are sufficient data to compare simulated with observed gradients, it is seen that the model performs reasonably well in reproducing the magnitude and direction of the observed gradients at almost all elements although there are some cases where the correspondence could be improved. It should be noted that some of the triangular elements used for hydraulic gradient evaluation are quite eccentric – that is, they are not close to equilateral – and that this can undermine conclusions regarding either simulated, or observed, hydraulic gradients and their correspondence.

The calibration results presented in this report should be considered the result of a continuous process of development, calibration, and validation of the 100AGWM that will continue following collation and incorporation of data collected as part of the River Corridor RI/FS process. For example, a large number of slug tests are have been conducted and analyzed throughout the River Corridor as part of the RI/FS process: these data will be incorporated in the 100AGWM in the next revision of the model.

Table 6-2. Mean Zonal Hydraulic Conductivity Values in the 100 Areas [m/d].

Unit	100-BC-5	100-KR-4	100-HR-3/D	100-HR-3/H	100-FR-3
Hanford	63.4	63.4	63.4	63.4	100
Ringold E	6.2	6.2	19.0	63.4	100

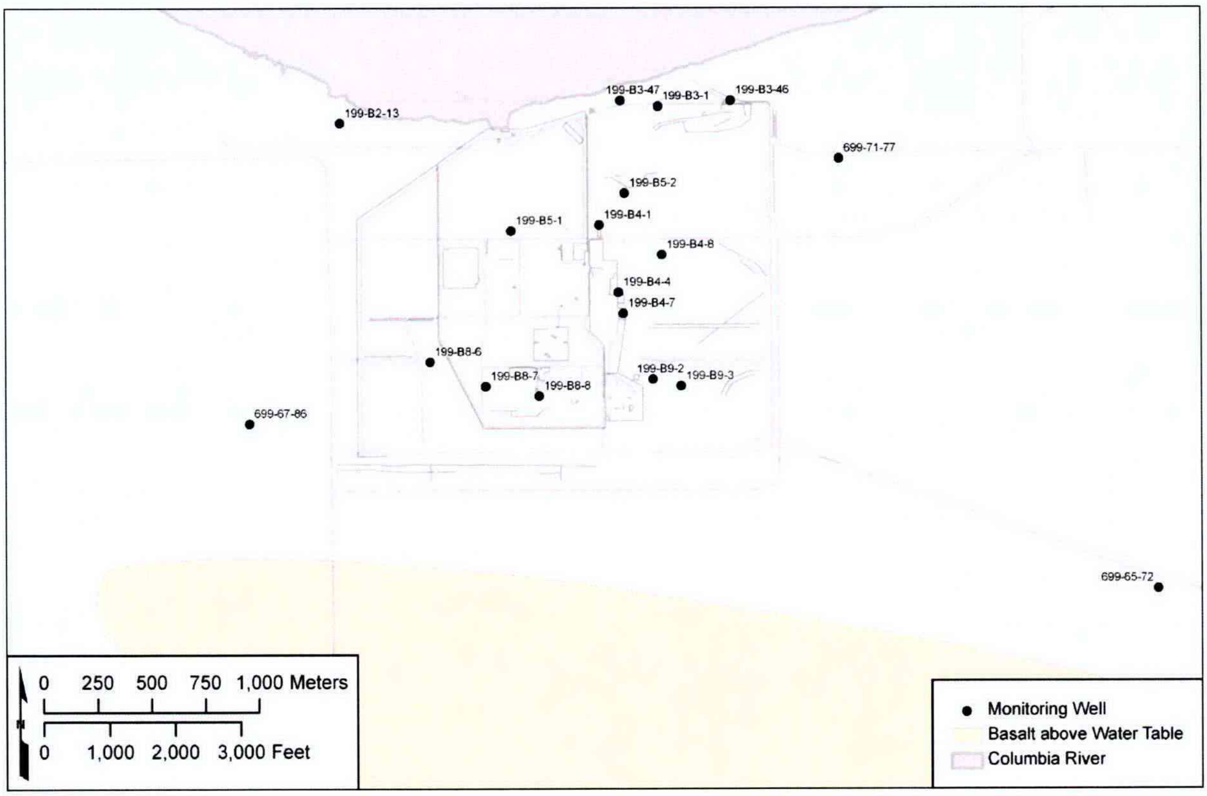


Figure 6-1. Monitoring Wells in 100-BC-5

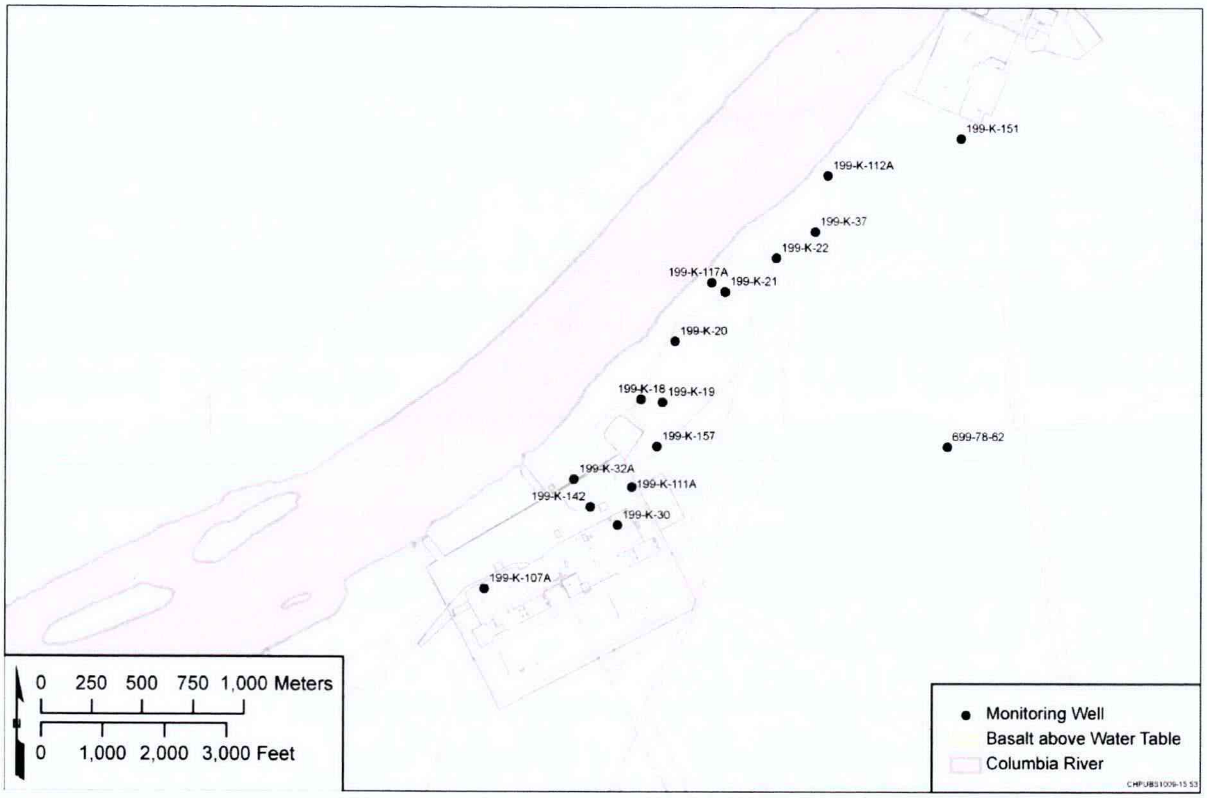


Figure 6-2. Monitoring Wells in 100-KR-4

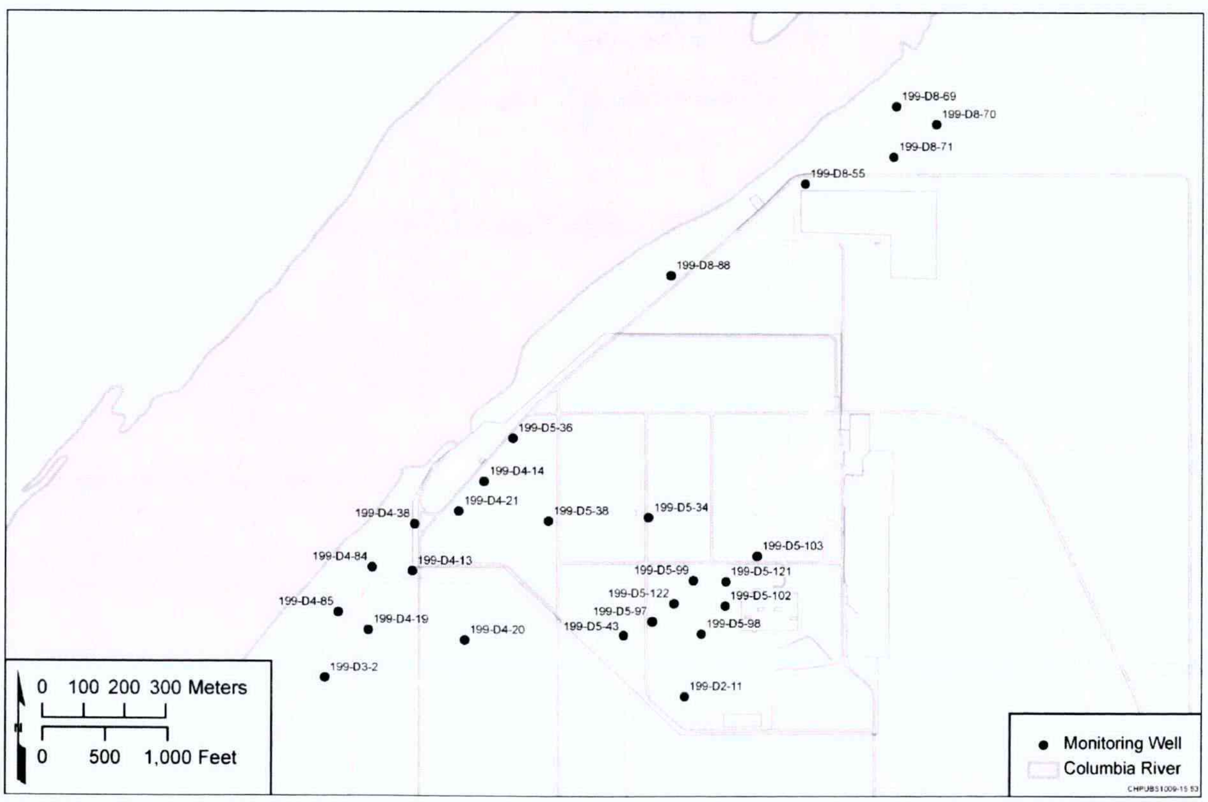


Figure 6-3. Monitoring Wells in 100-HR-3-D

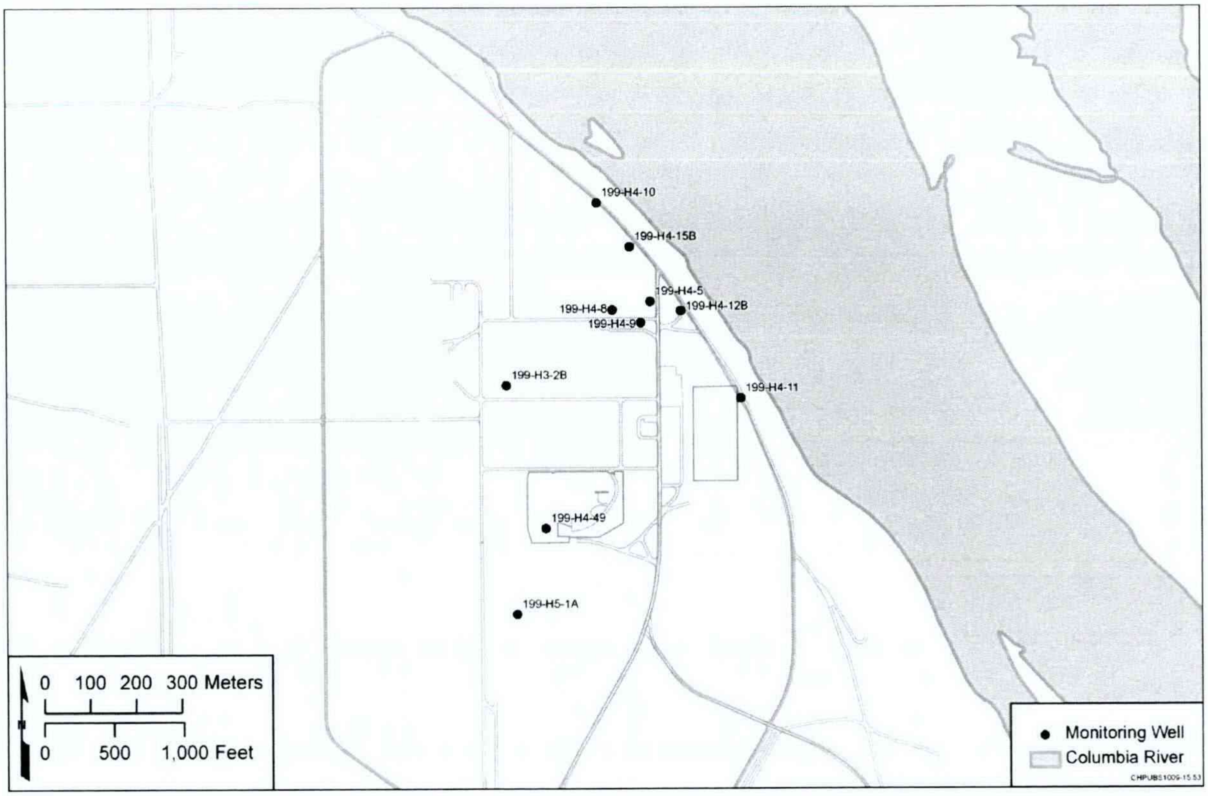


Figure 6-4. Monitoring Wells in 100-HR-3-H

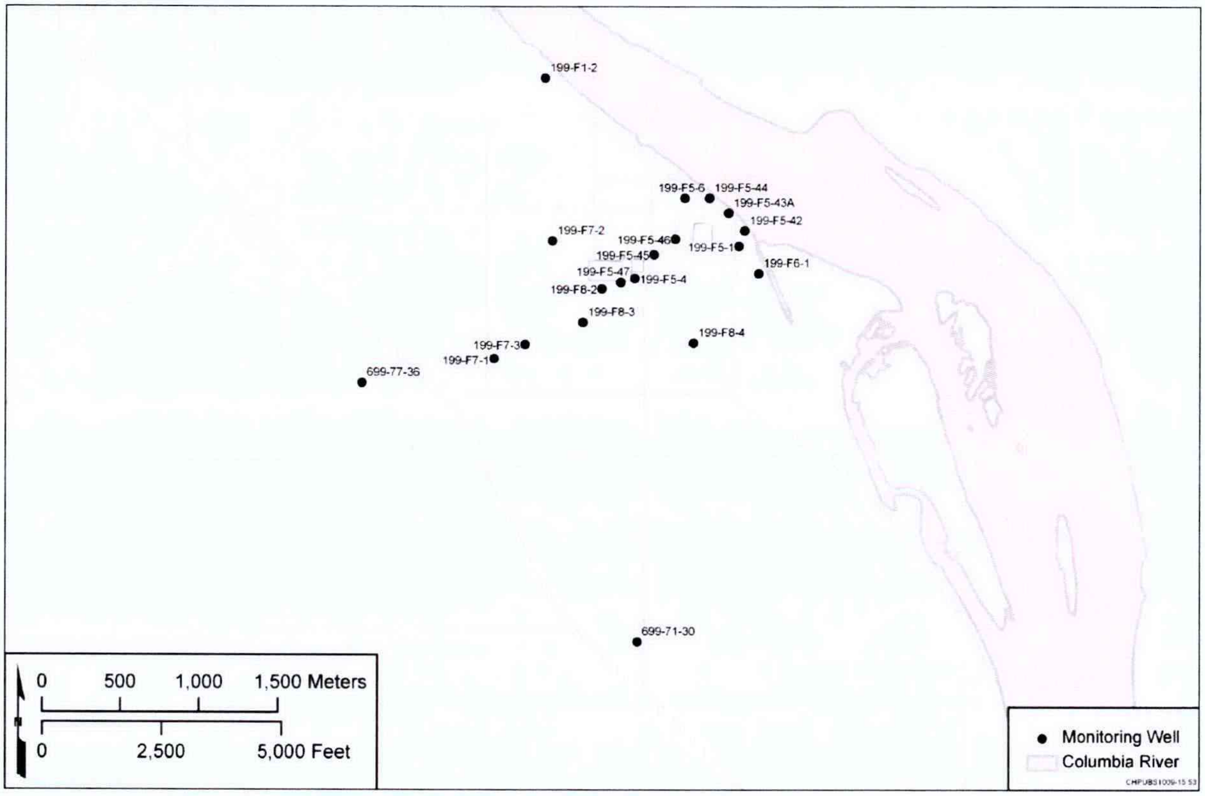


Figure 6-5. Monitoring Wells in 100-FR-3

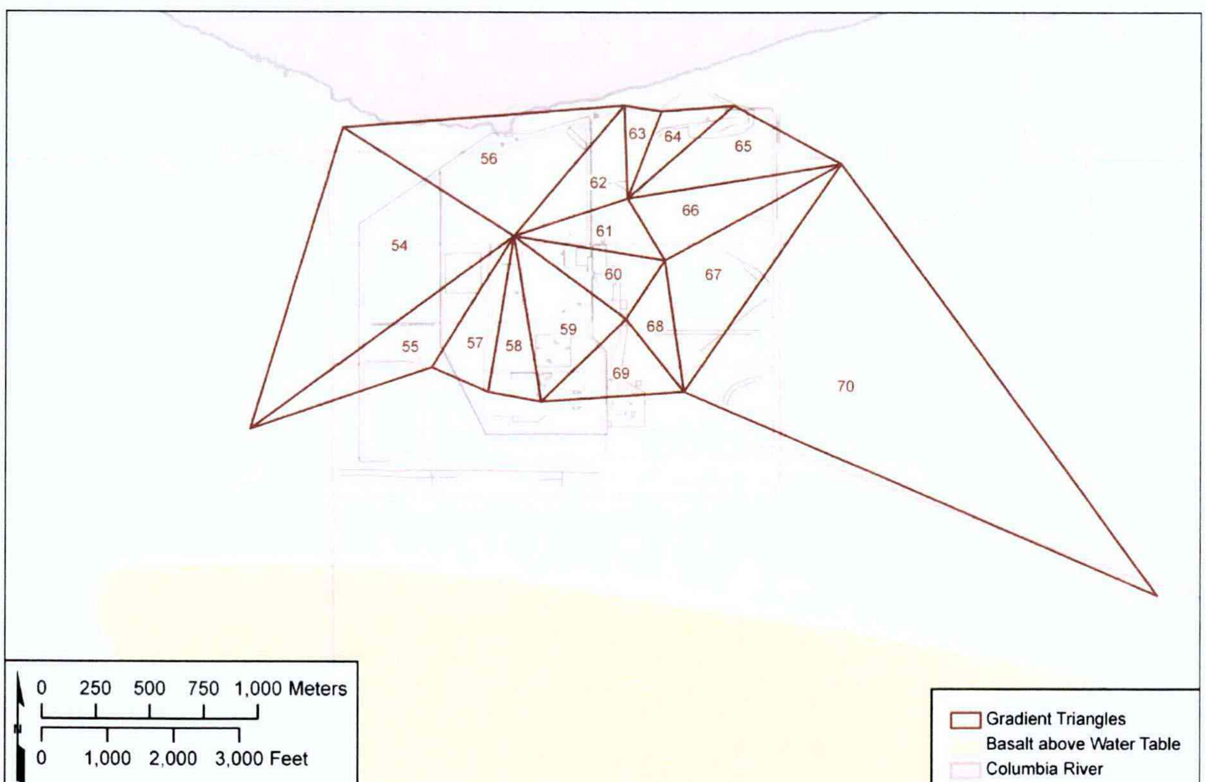


Figure 6-6. Triangular elements for gradient calculation in 100-BC-5

Figure 6-7. Triangular elements for gradient calculation in 100-KR-4

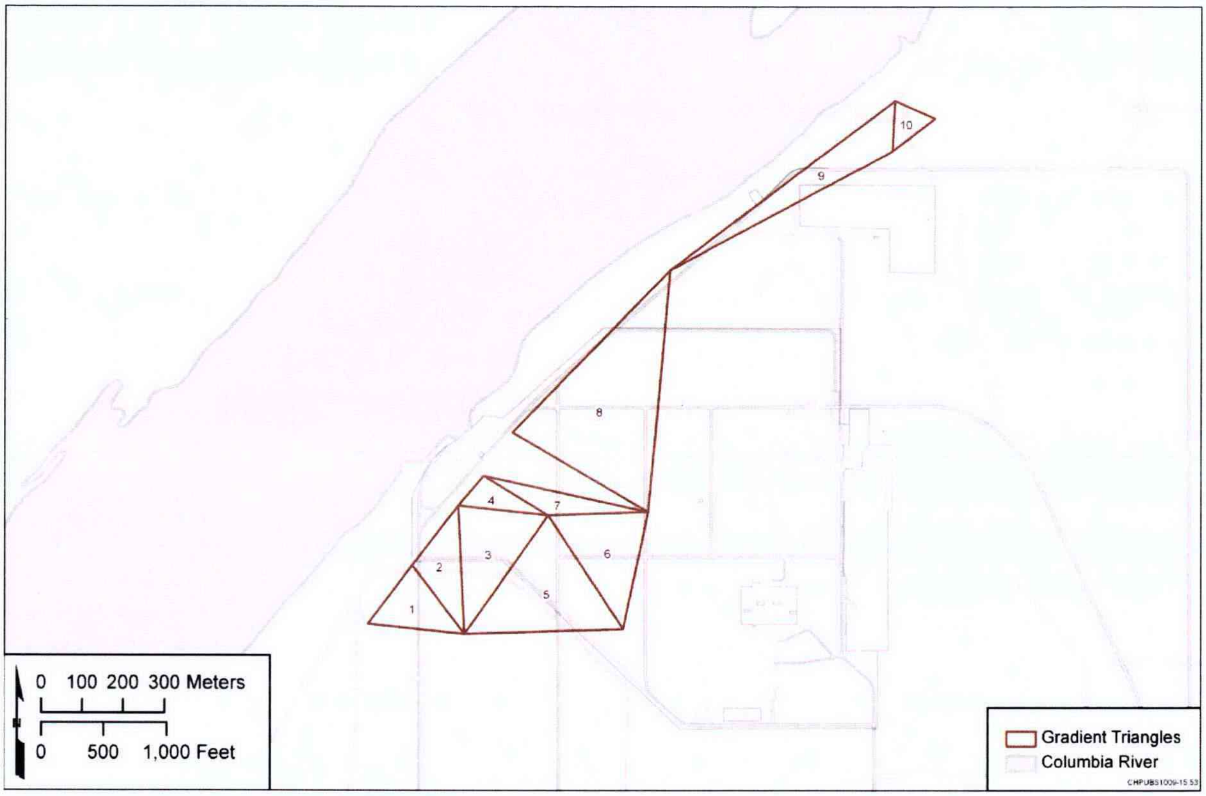


Figure 6-8. Triangular elements for gradient calculation in 100-HR-3-D

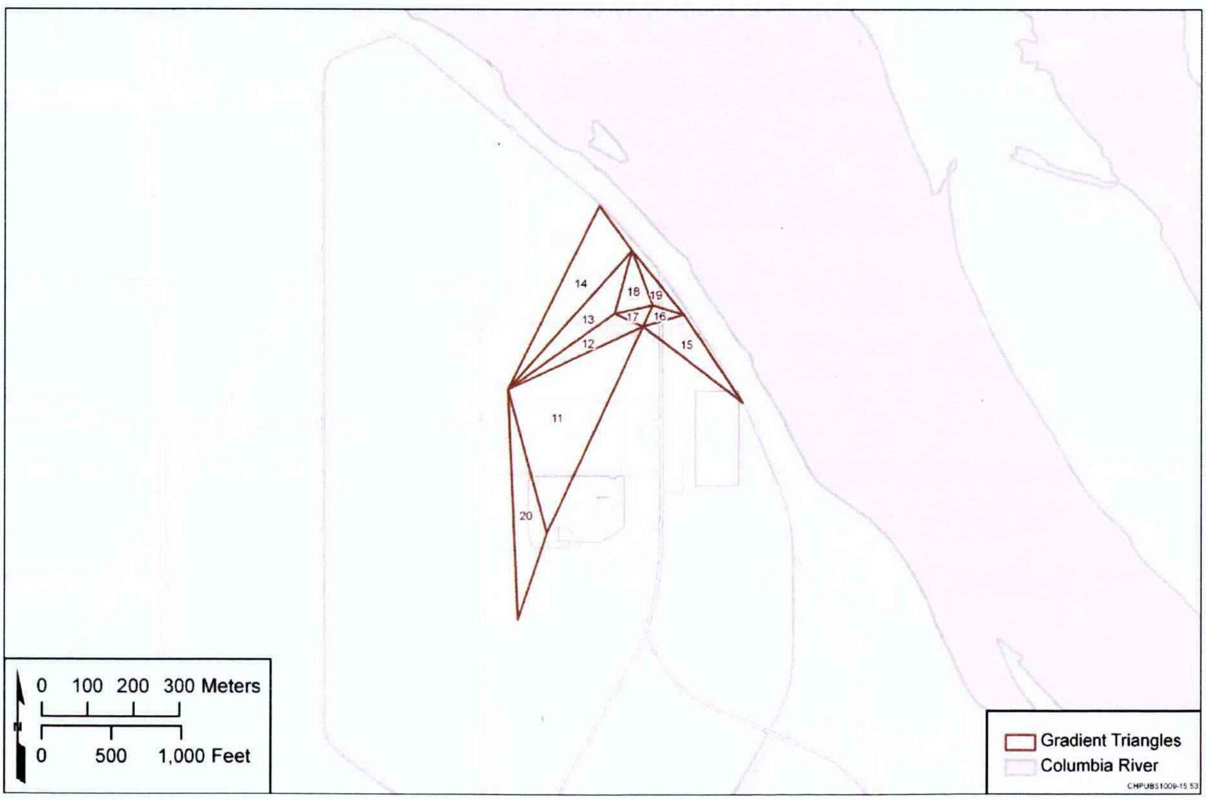


Figure 6-9. Triangular elements for gradient calculation in 100-HR-3-H

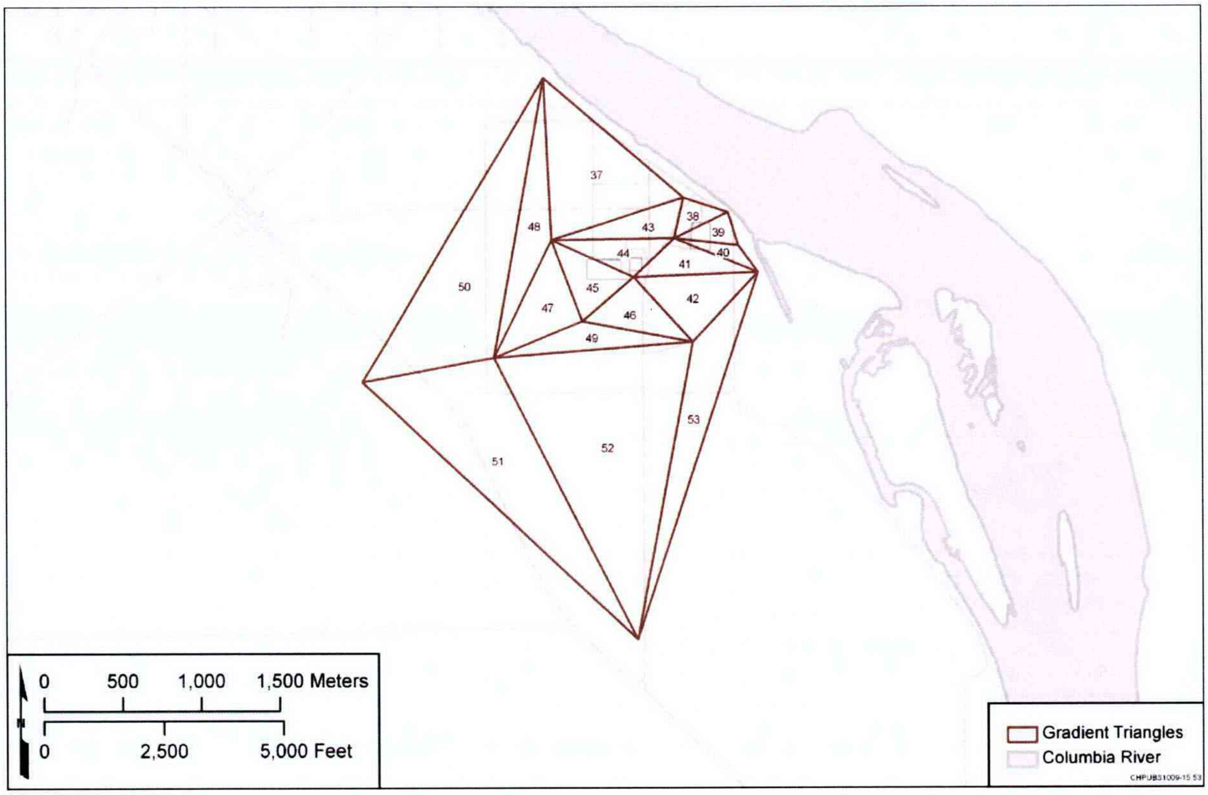


Figure 6-10. Triangular elements for gradient calculation in 100-FR-3

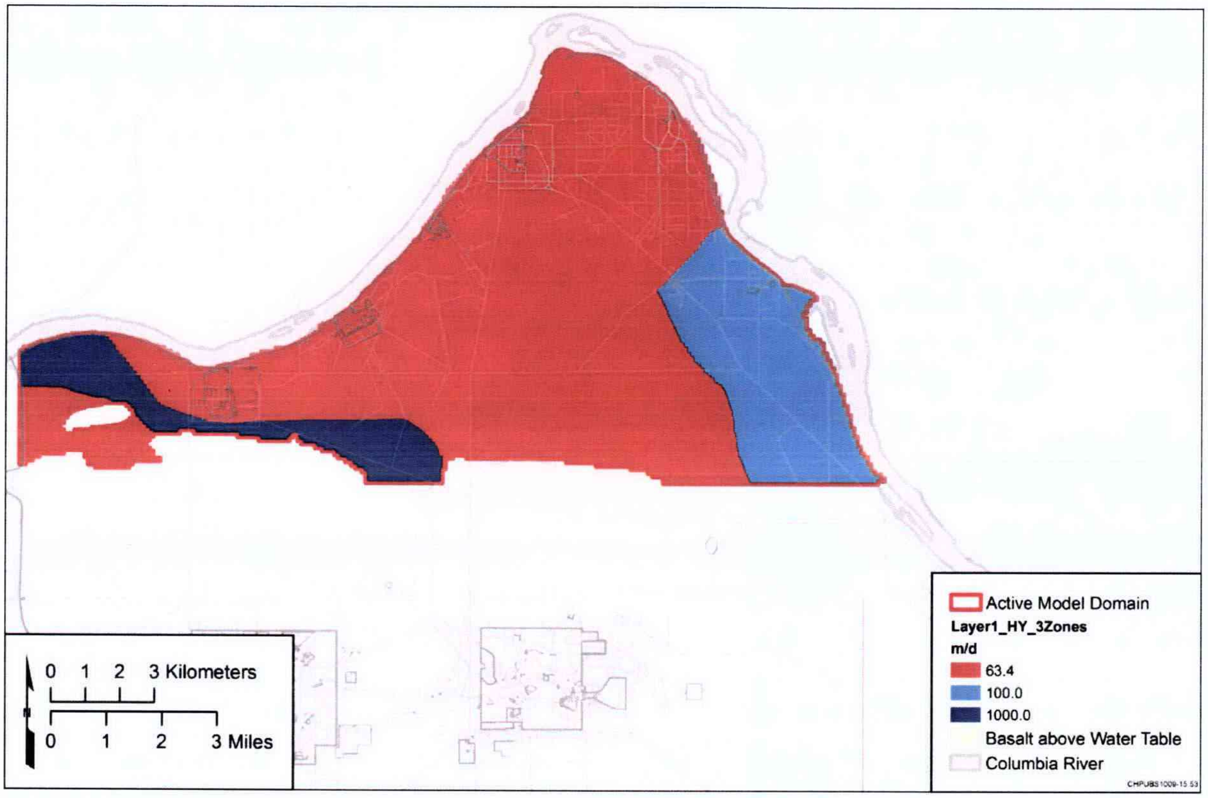


Figure 6-11. Hydraulic Conductivity Distribution: Hanford formation.

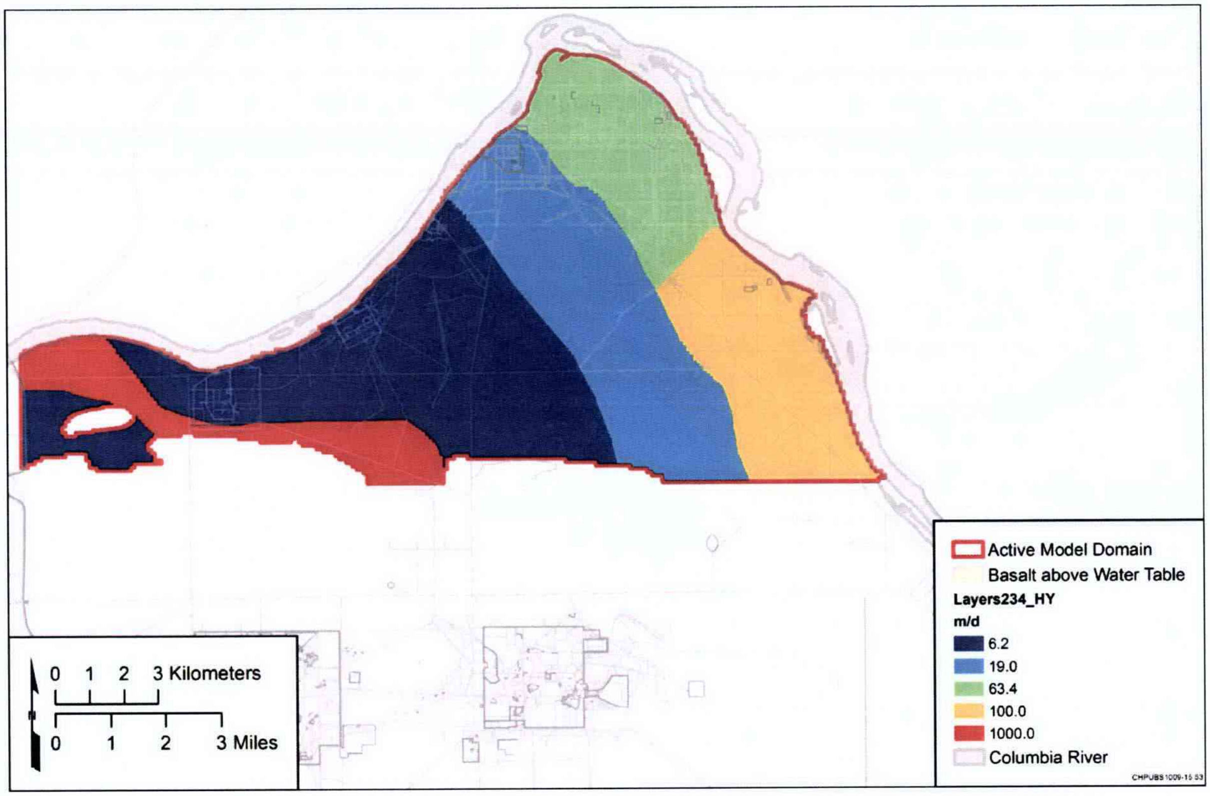


Figure 6-12. Hydraulic Conductivity for Ringold E formation

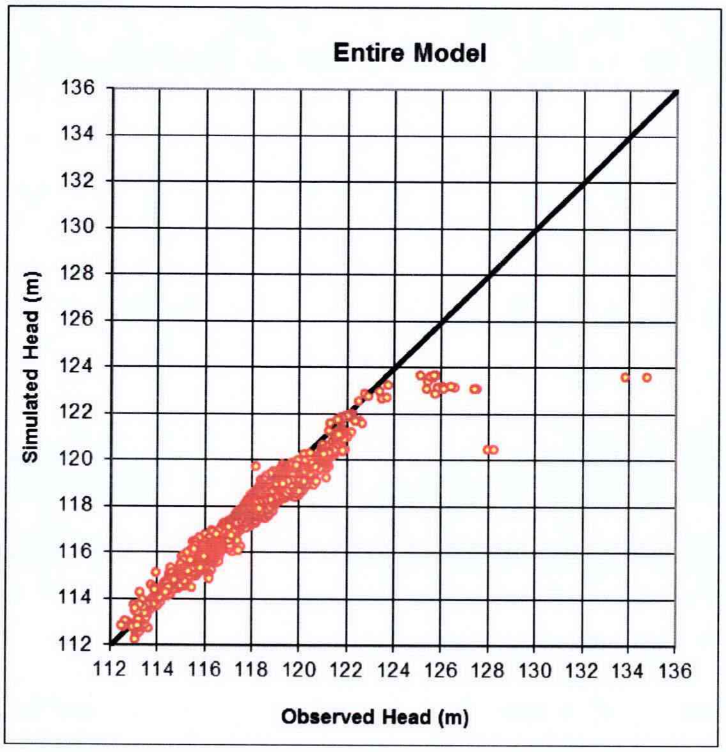


Figure 6-13. Measured versus Calculated Water Levels across the Model Domain

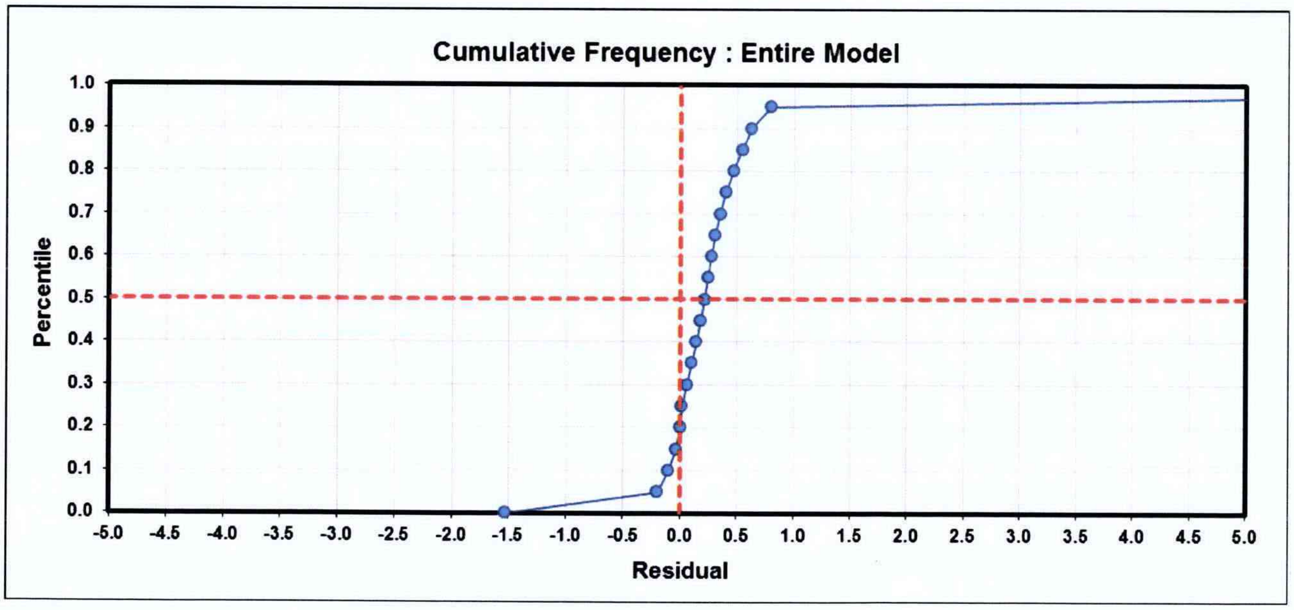


Figure 6-14. Cumulative Frequency of the Water Level Residuals across the Model Domain

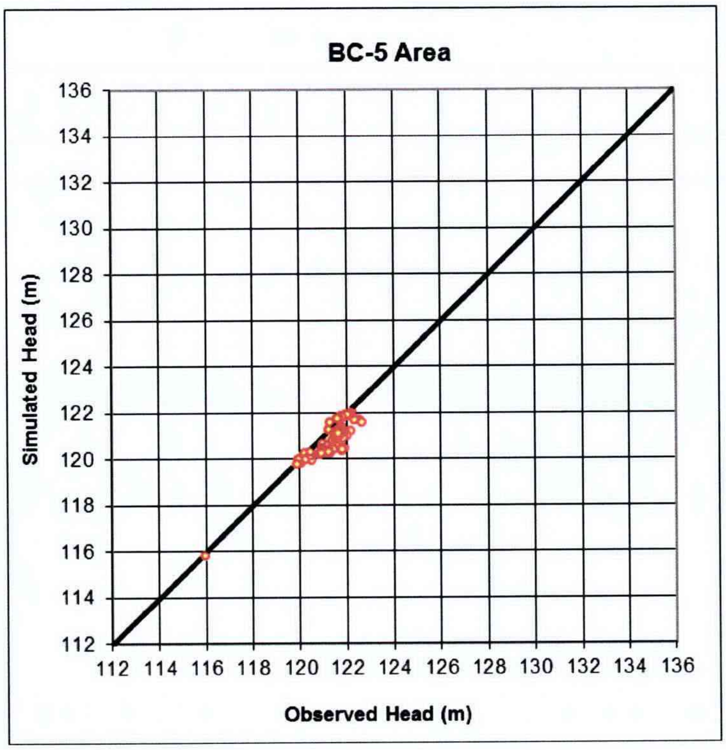


Figure 6-15. Measured versus Calculated Water Levels in 100-B/C.

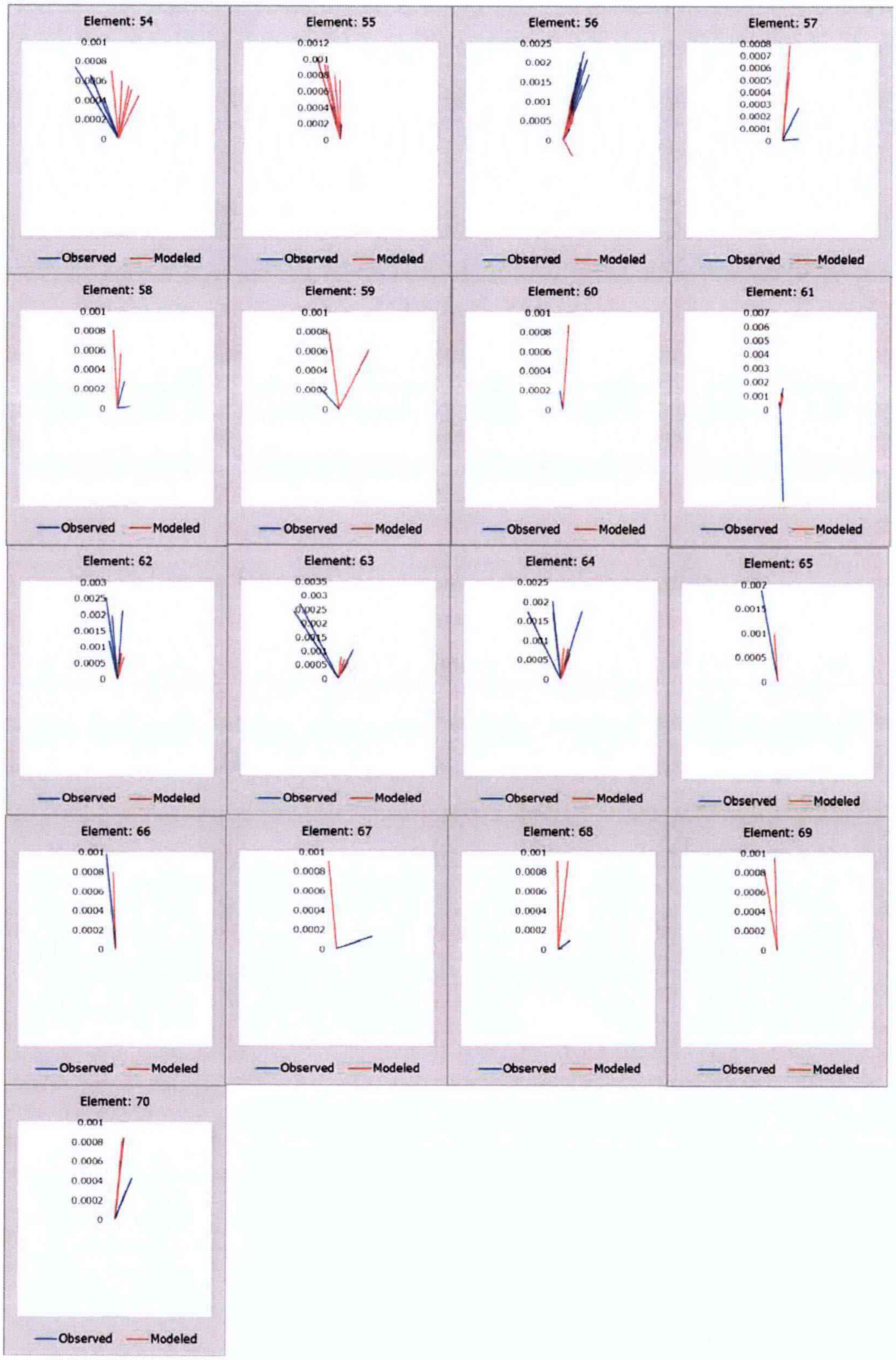


Figure 6-16. Measured versus Calculated Hydraulic Gradients in 100-B/C.

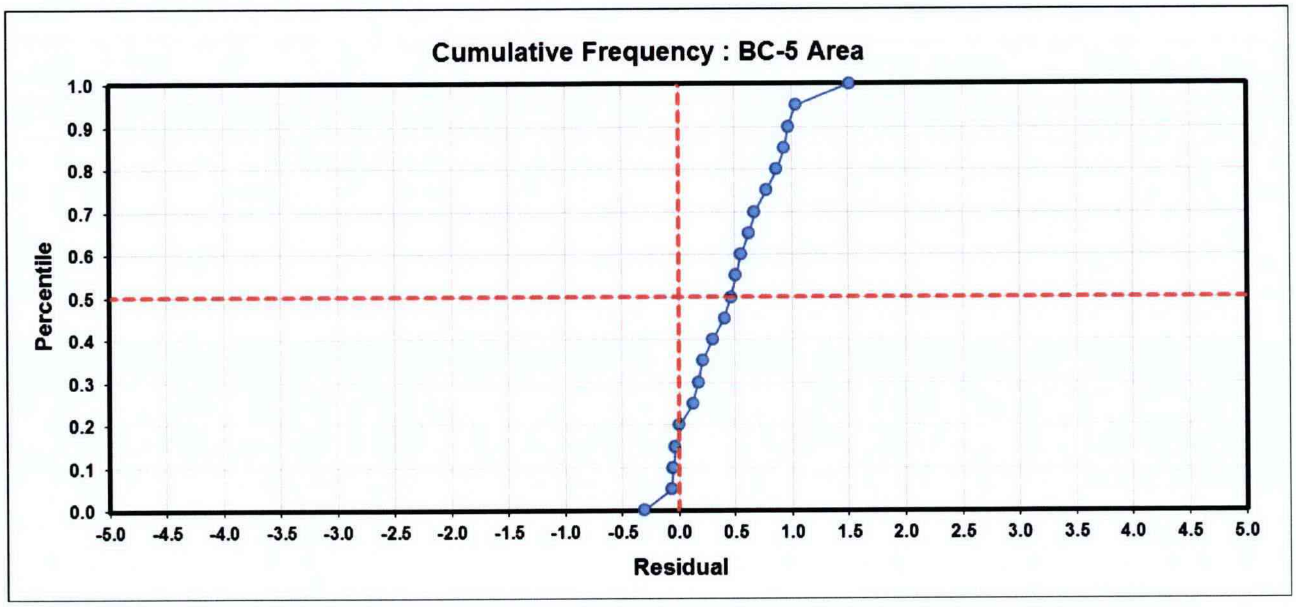


Figure 6-17. Cumulative Frequency of the Water Level Residuals in 100-B/C.

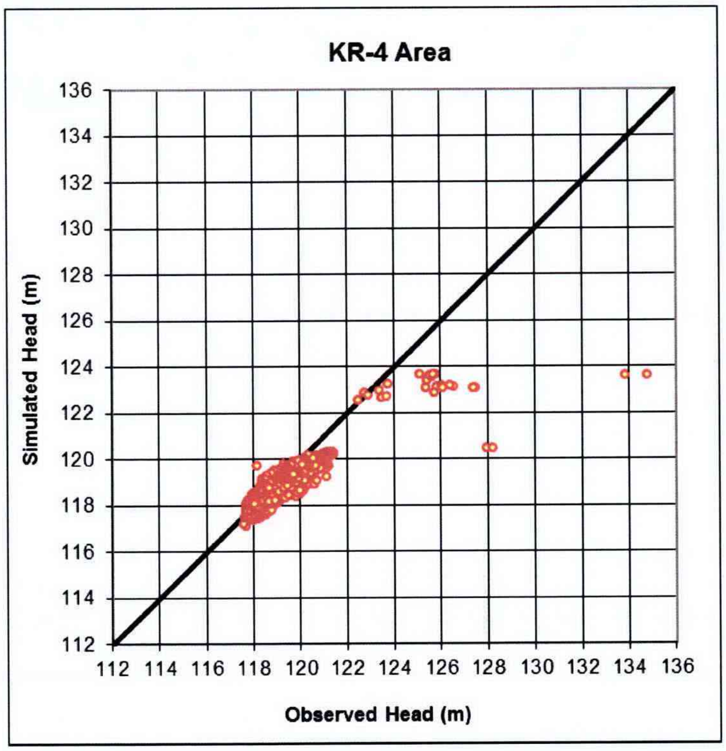
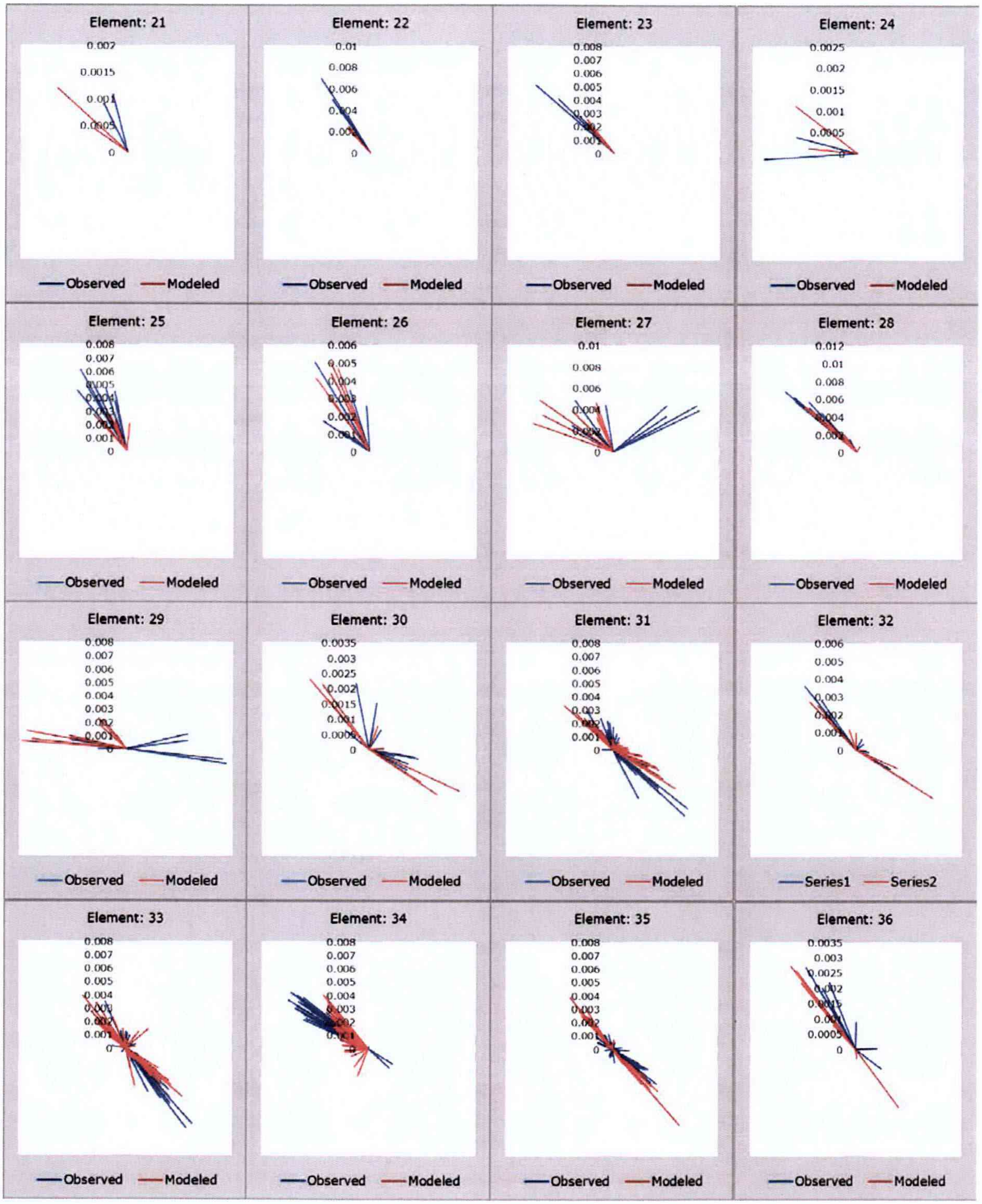


Figure 6-18. Measured versus Calculated Water Levels in 100-K.



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2 **Figure 6-19. Measured versus Calculated Hydraulic Gradients in 100-K.**

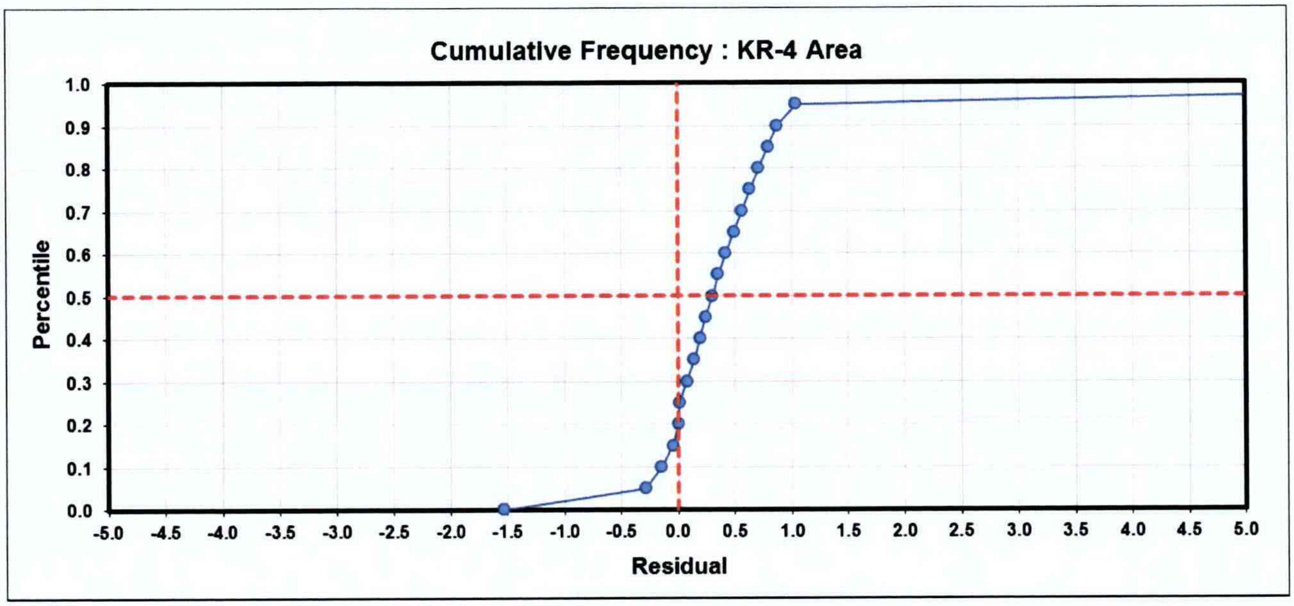

Figure 6-20. Cumulative Frequency of the Water Level Residuals in 100-K.

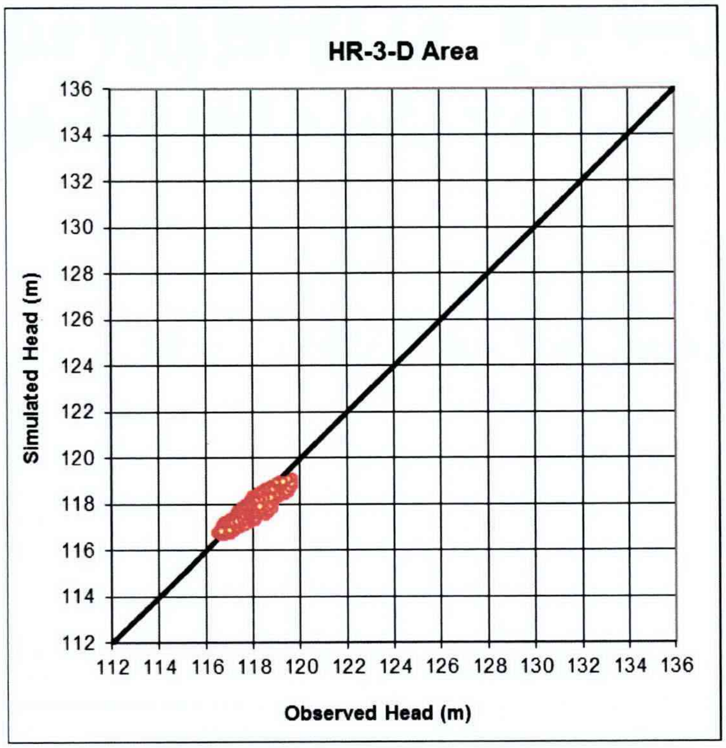

Figure 6-21. Measured versus Calculated Water Levels in 100-D.

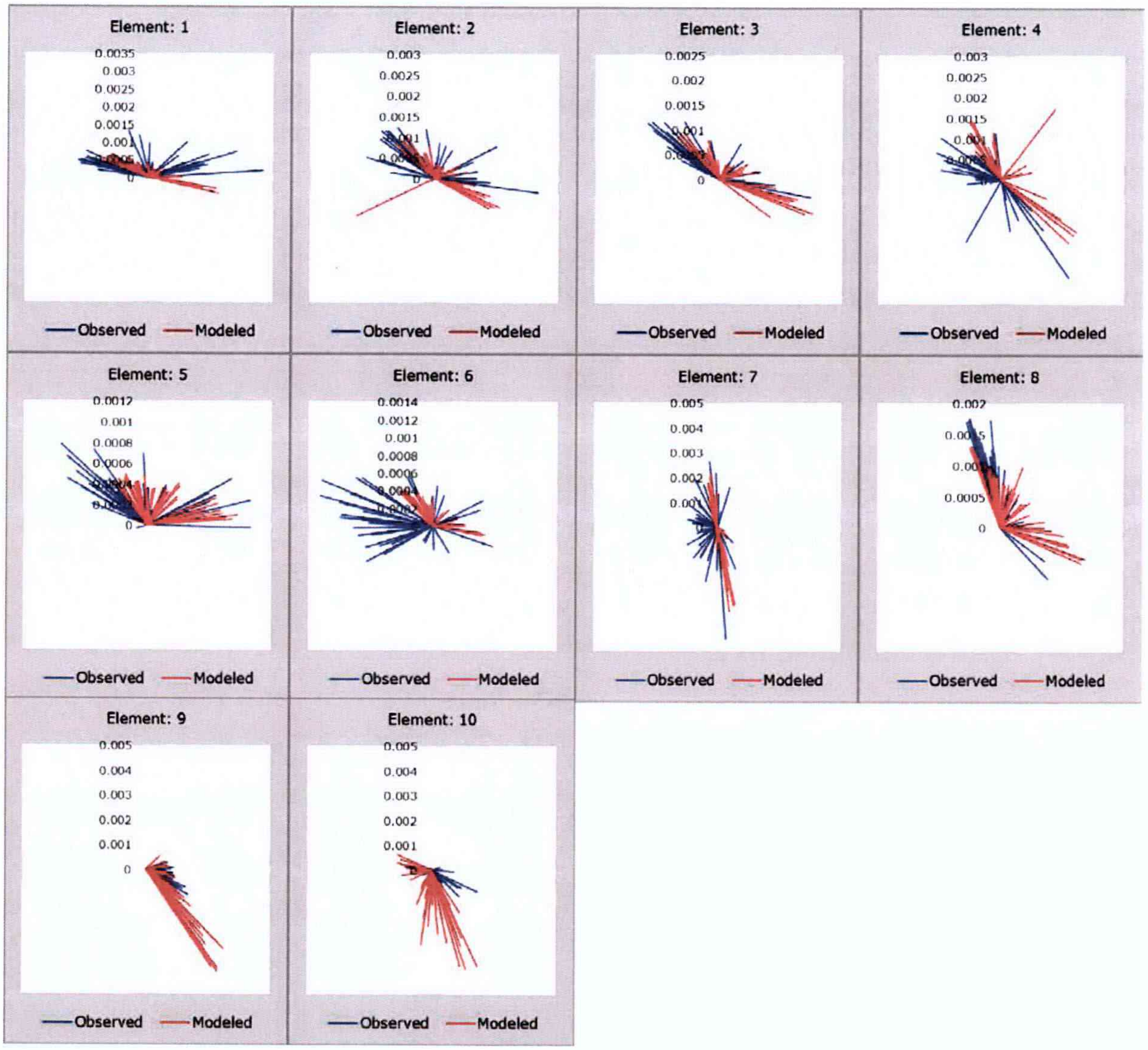

Figure 6-22. Measured versus Calculated Hydraulic Gradients in 100-D.

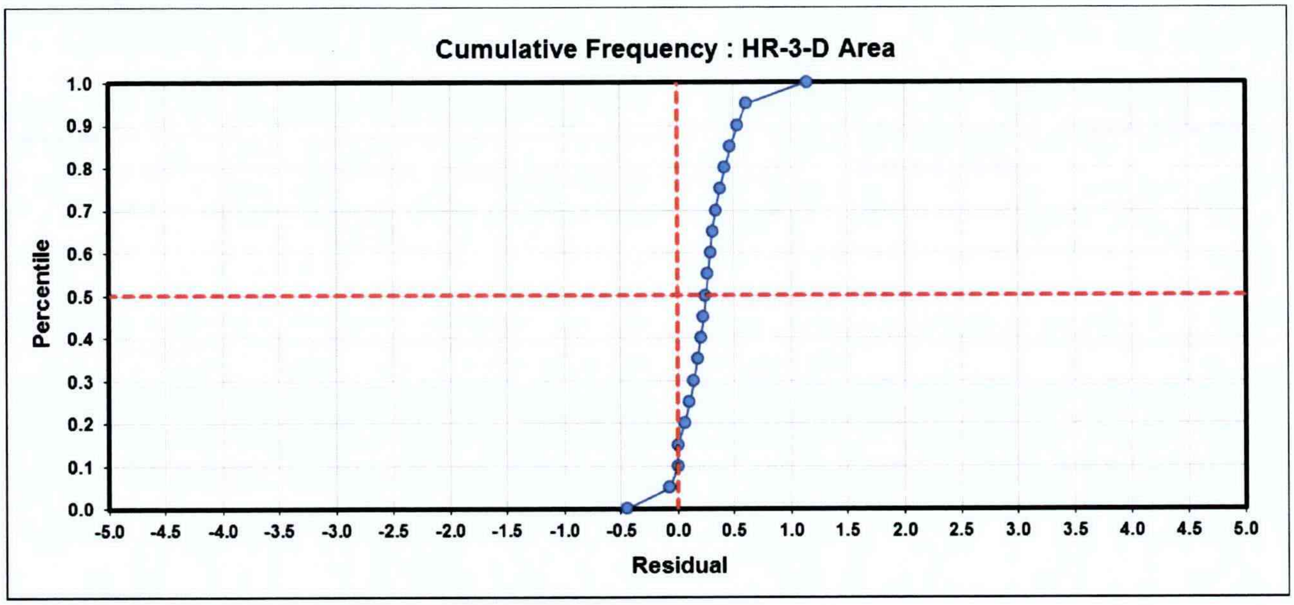

Figure 6-23. Cumulative Frequency of the Water Level Residuals in 100-D.

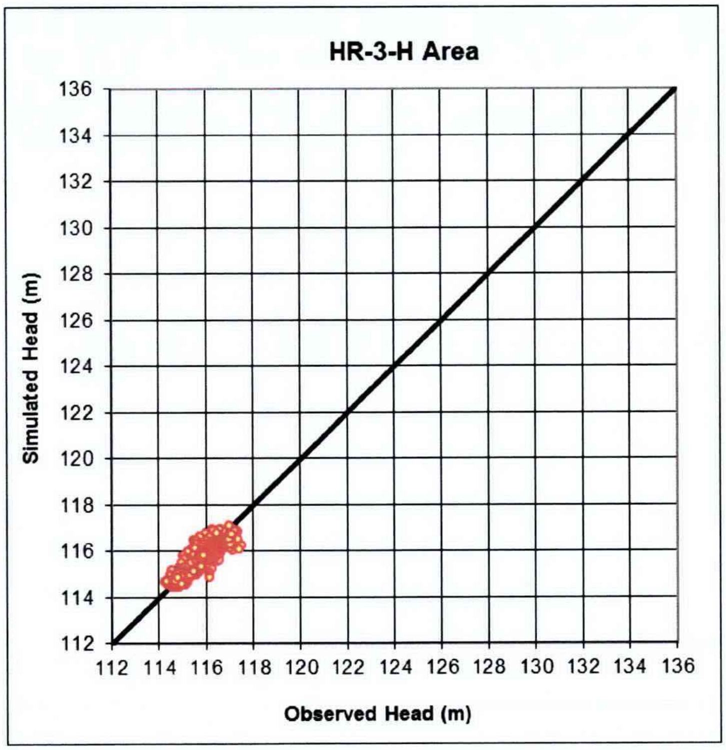

Figure 6-24. Measured versus Calculated Water Levels in 100-H.

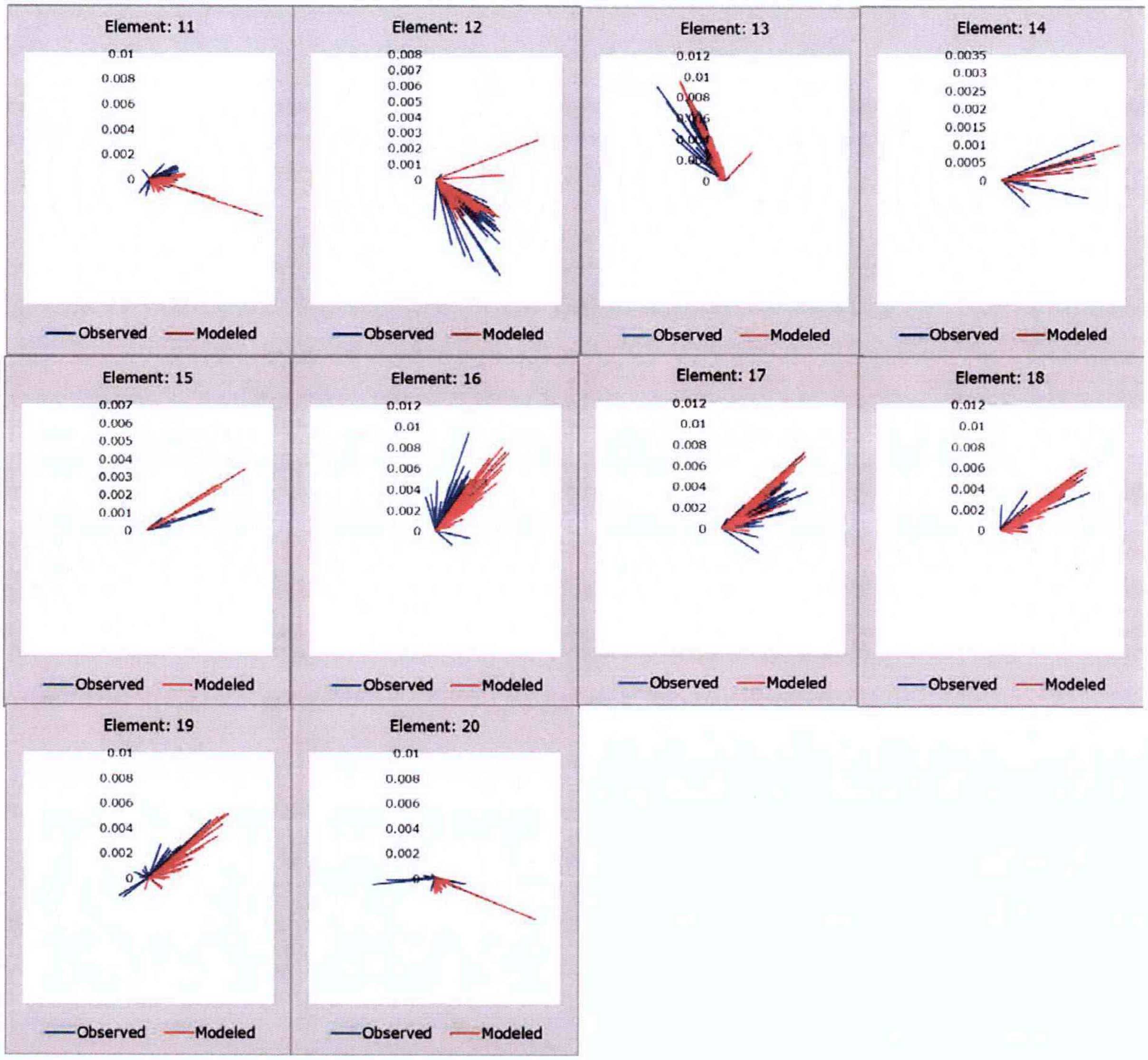

Figure 6-25. Measured versus Calculated Hydraulic Gradients in 100-H.

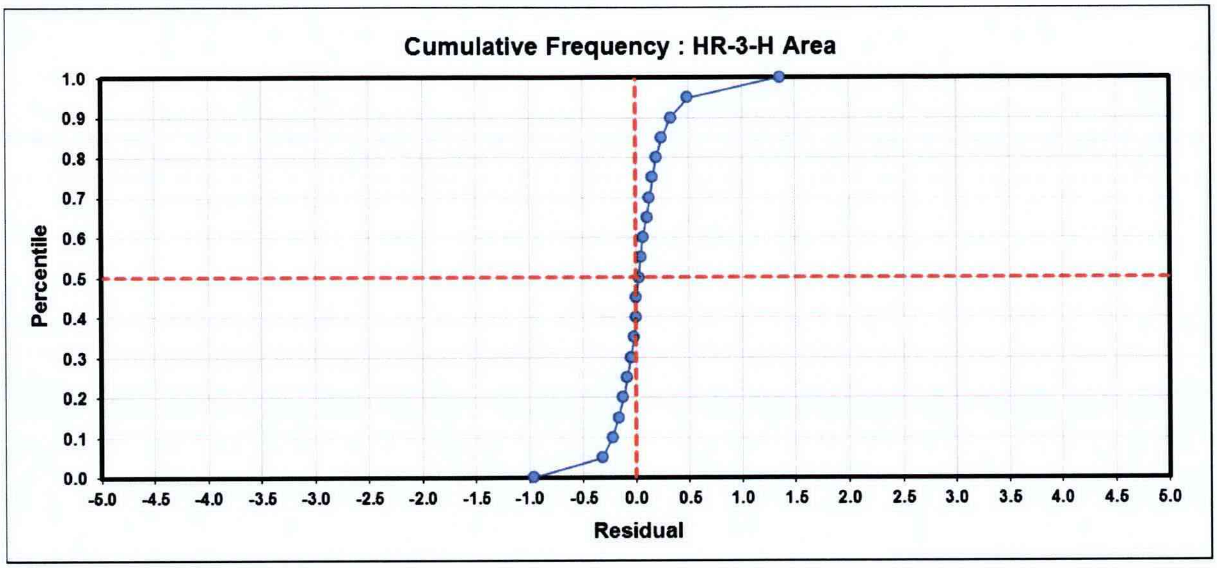

Figure 6-26. Cumulative Frequency of the Water Level Residuals in 100-H.

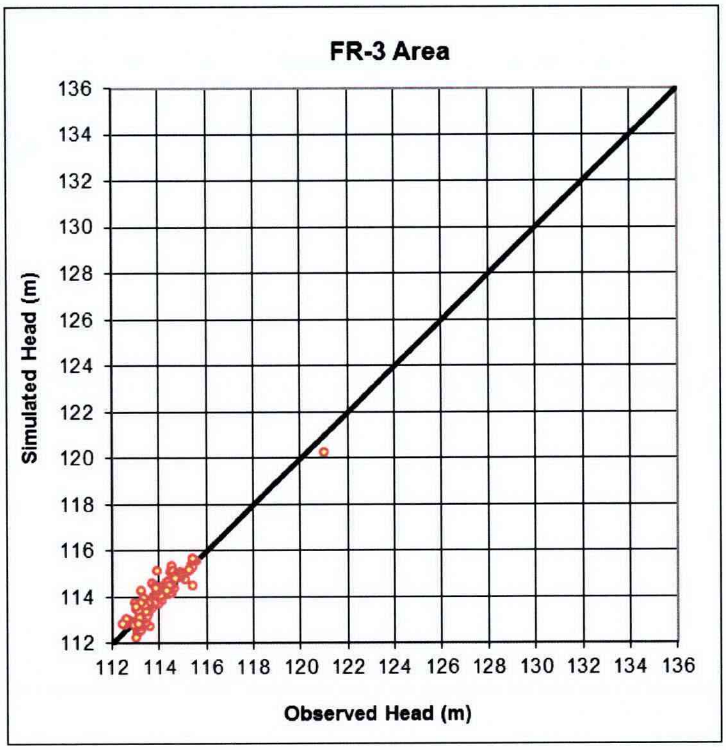

Figure 6-27. Measured versus Calculated Water Levels in 100-F.

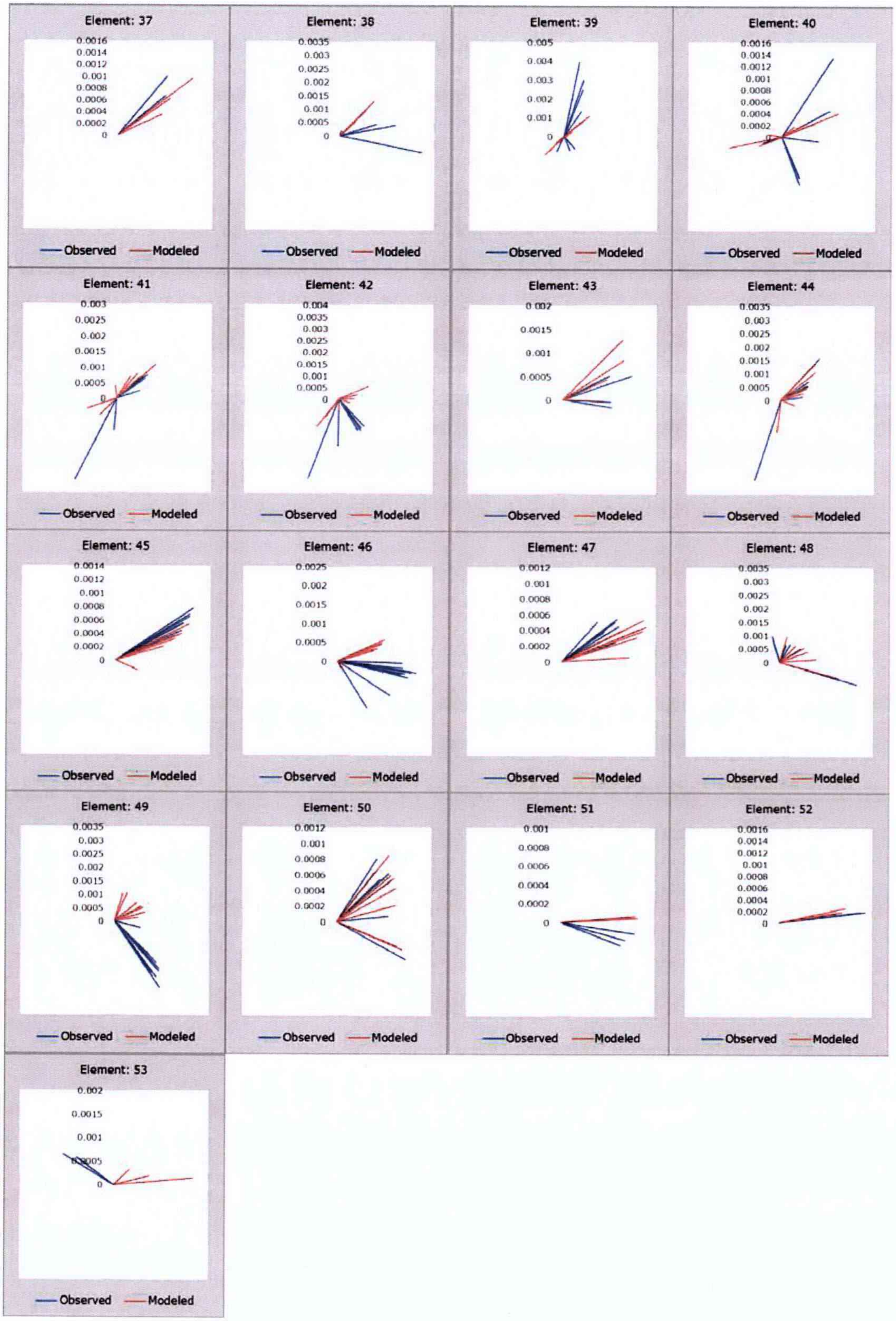

Figure 6-28. Measured versus Calculated Hydraulic Gradients in 100-F.

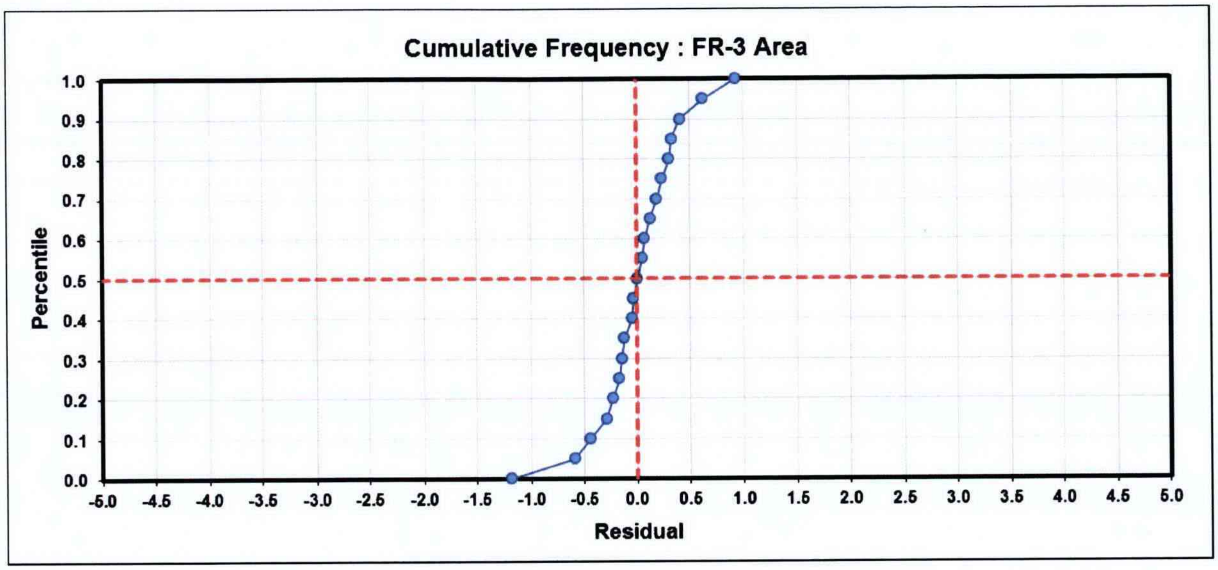

Figure 6-29. Cumulative Frequency of the Water Level Residuals in 100-FR-3

7 Flow Model Validation

For purposes of this report, the process of model validation is defined as the comparison of model outputs with data that were either purposefully excluded from, or not available at the time of, the model calibration to determine whether the model reproduces these data as (or more) satisfactorily than the calibration data. Doing so is one line of evidence that the parameters identified through model calibration are not only suitable for the calibration period and data sets, but are also applicable to other periods and data sets.

The groundwater flow component of the 100AGWM was validated to data from throughout the period July 2009 to December 2010. The model validation process focused on the transient response of water levels to changing stresses and how they compared to the measured values at locations for which continuous water level data were available at the 100-K, 100-D, and 100-H Areas. The aquifer response was also evaluated in 100-B/C and 100-F where only manual water level measurements are available for the validation period.

Table 7-1 includes the same statistical metrics that were used for the evaluation of model calibration, summarized for the validation period. The mean error is 0.21 m and the mean squared error is 0.63 m^2. The RMSE is 0.40 m, and the R^2 is 0.97 - suggesting that the measured and calculated water levels are highly correlated. The positive average residual indicates that the model slightly underestimates water levels across the model domain during the validation period, consistent with what was observed during the calibration period. The low RMSE value suggests a reasonable fit between the measured and calculated water levels.

As for the calibration period, however, visual assessment of the calibration results may be more informative. Scatter plots of observed versus simulated water levels are shown in Figures 7-1 (for the entire model domain), 7-3 (100-B/C), 7-5 (100-K), 7-7 (100-D), 7-9 (100-H) and 7-11 (100-F). Cumulative frequency plots of the water level residuals are illustrated in Figures 7-2 (for the entire model domain), 7-4 (100-B/C), 7-6 (100-K), 7-8 (100-D), 7-10 (100-H) and 7-12 (100-F). The summary statistics, scatter plots and residual cumulative frequency plots for each OU suggest that model behavior is consistent between the calibration and validation periods.

Table 7-1. Validation Statistics.

Metric	100 Area	100-B/C	100-K	100-D	100-H	100-F
Coefficient of Correlation	0.97	0.83	0.84	0.91	0.87	0.93
R^2	0.94	0.68	0.71	0.84	0.76	0.87
Average Residual (m)	0.21	0.51	0.27	0.19	0.11	0.13
Maximum Residual (m)	1.68	1.10	1.68	1.05	1.19	1.15
Minimum Residual (m)	-1.58	-0.36	-1.58	-0.42	-1.01	-0.66
Sum of Squared Errors (SSE, m^2)	4131.3	34.0	2773.7	897.3	412.3	13.1
Mean Squared Error (MSE, m^2)	0.63	0.80	0.75	0.52	0.56	0.62
Root Mean Squared Error (RMSE, m)	0.40	0.64	0.57	0.27	0.31	0.39
Observed Range (m)	11.10	2.55	6.33	3.20	3.46	2.91
RMSE / Observed Range (%)	3.65%	25.07%	9.08%	8.44%	8.86%	13.41%

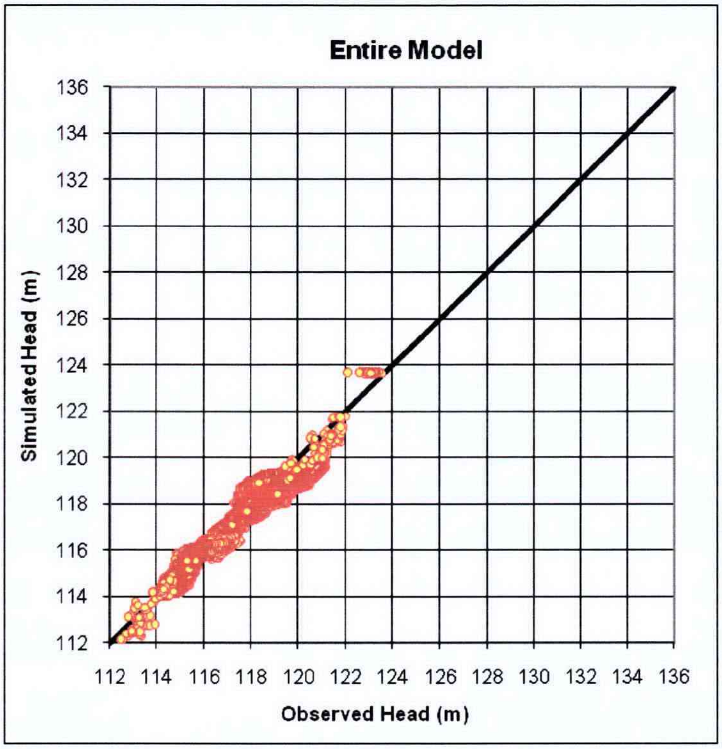

Figure 7-1. Measured versus Calculated Water Levels: Model Validation

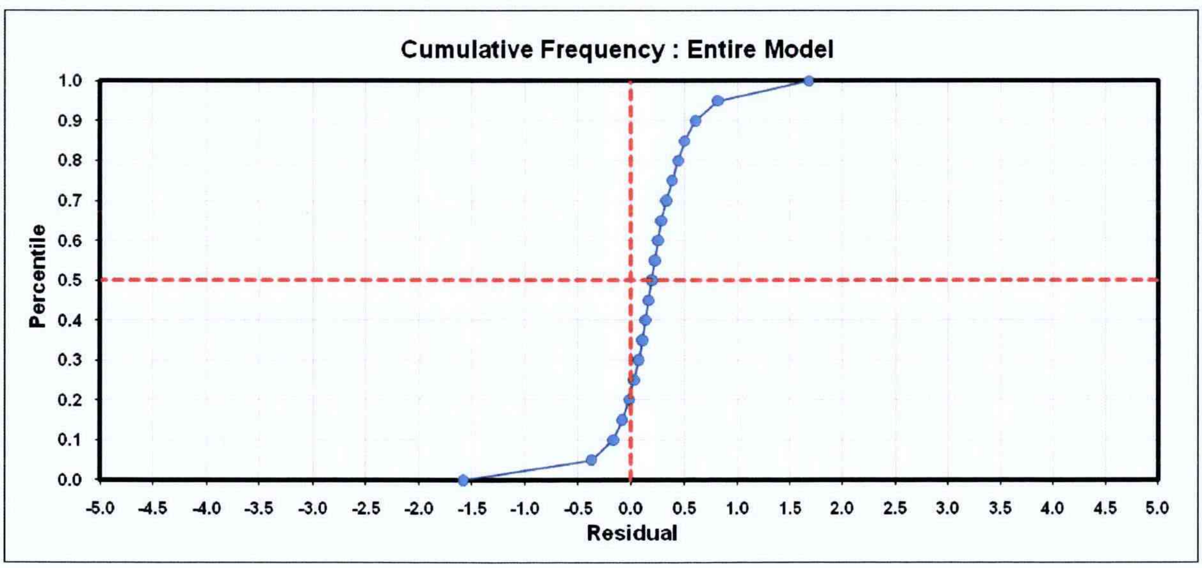

Figure 7-2. Cumulative Frequency of the Water Level Residuals: Model Validation.

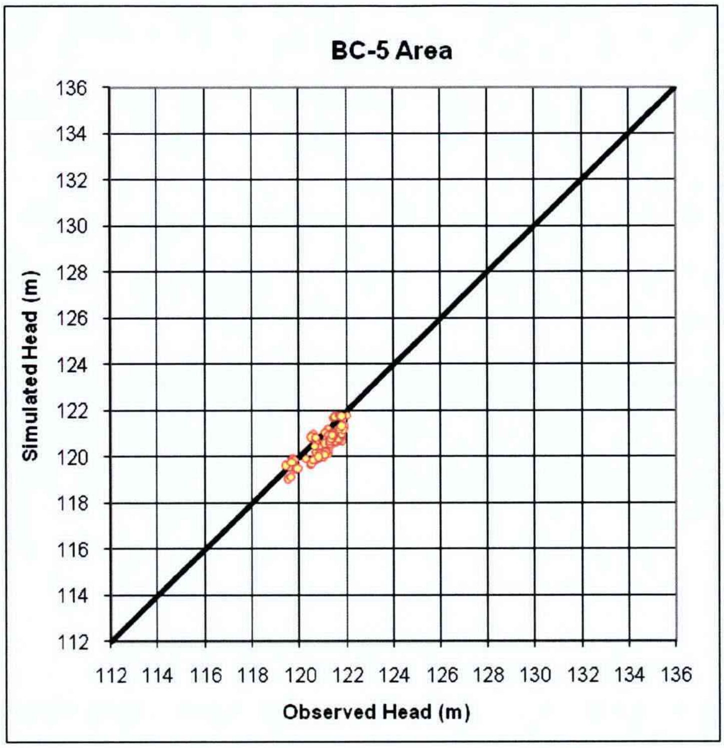

Figure 7-3. Measured versus Calculated Water Levels in 100-B/C: Model Validation.

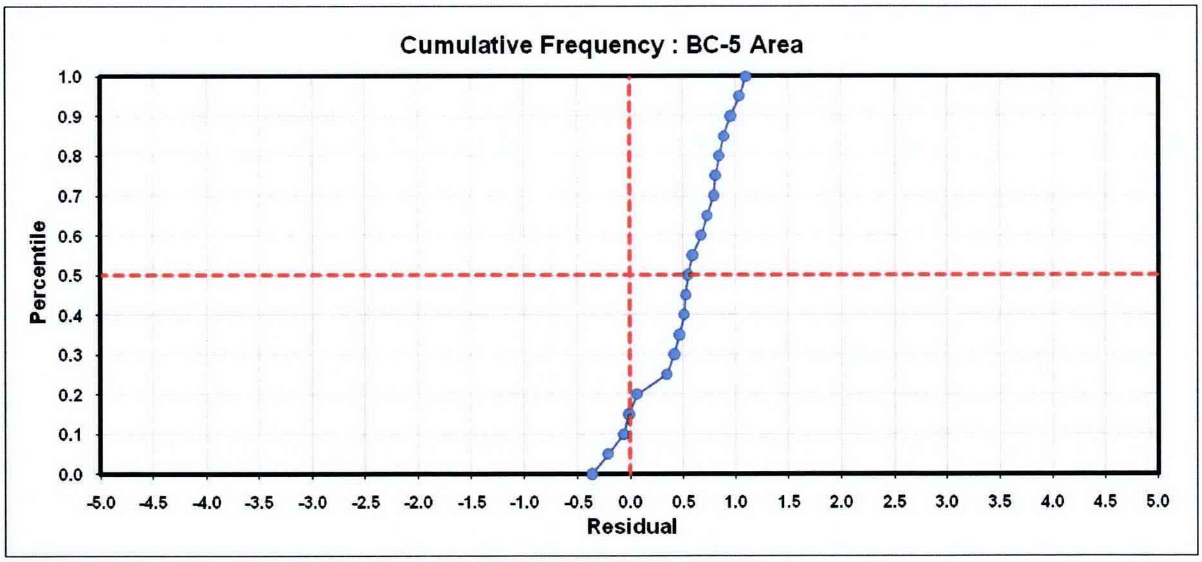

Figure 7-4. Cumulative Frequency of the Water Level Residuals in 100-B/C: Model Validation.

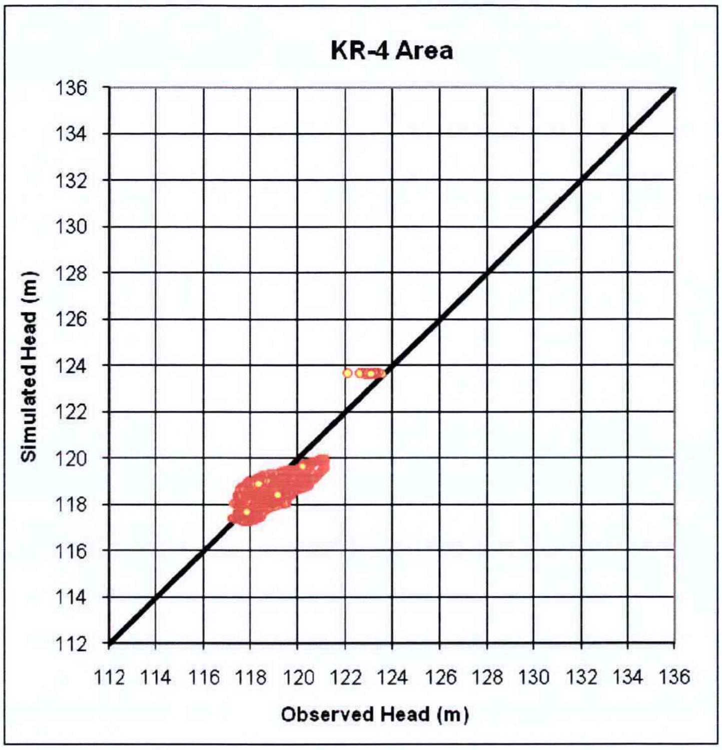

Figure 7-5. Measured versus Calculated Water Levels in 100-K: Model Validation.

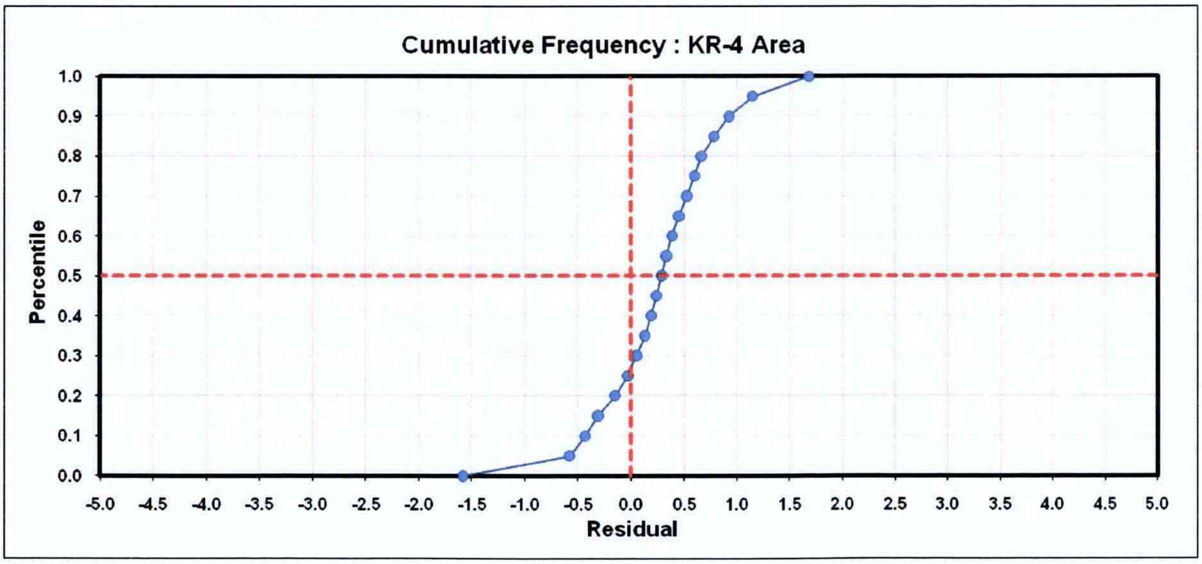

Figure 7-6. Cumulative Frequency of the Water Level Residuals in 100-K: Model Validation.

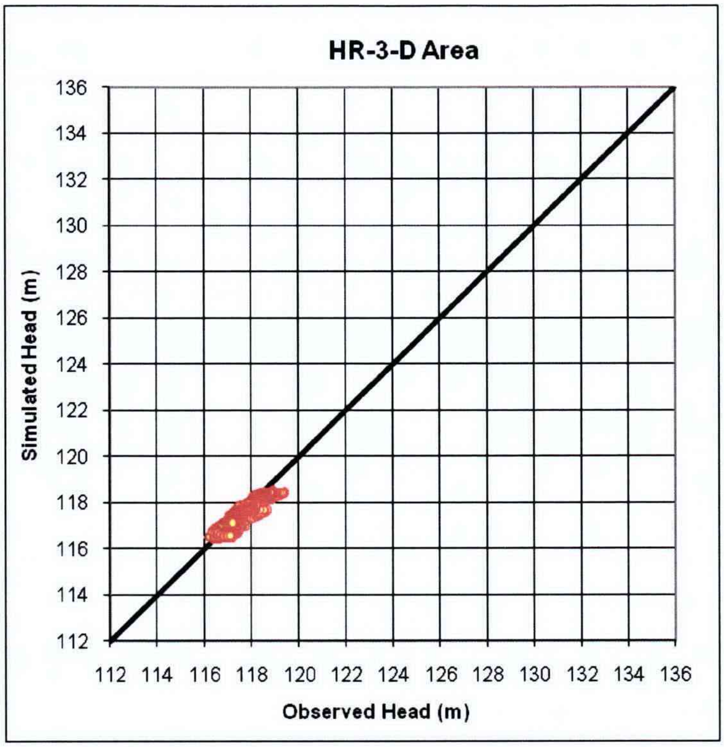

Figure 7-7. Measured versus Calculated Water Levels in 100-D: Model Validation.

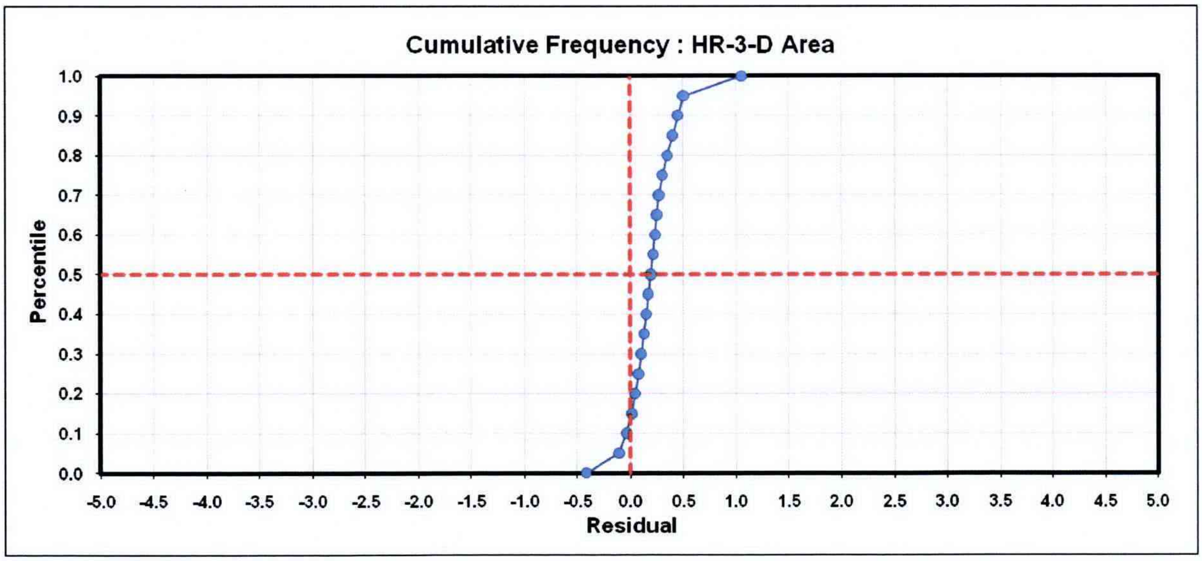

Figure 7-8. Cumulative Frequency of the Water Level Residuals in 100-D: Model Validation.

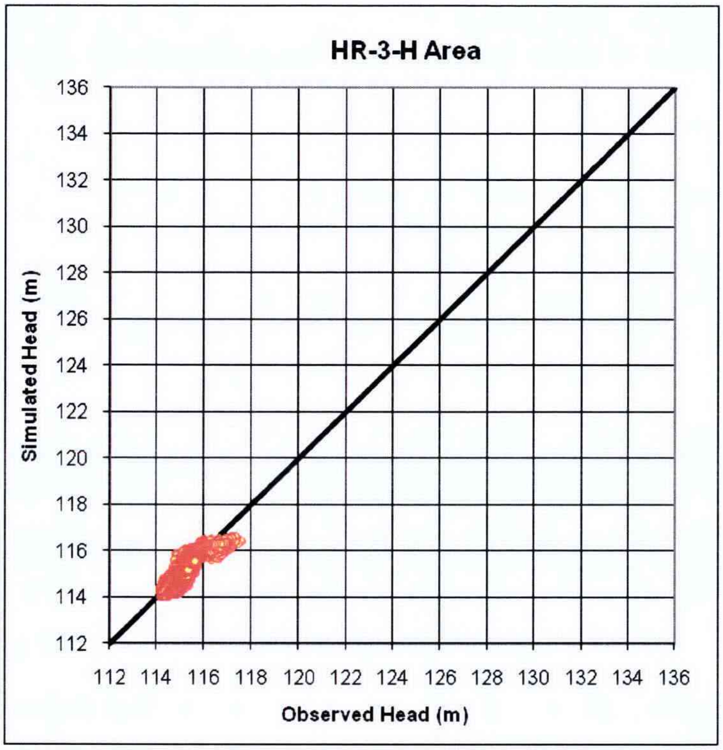

Figure 7-9. Measured versus Calculated Water Levels in 100-H: Model Validation.

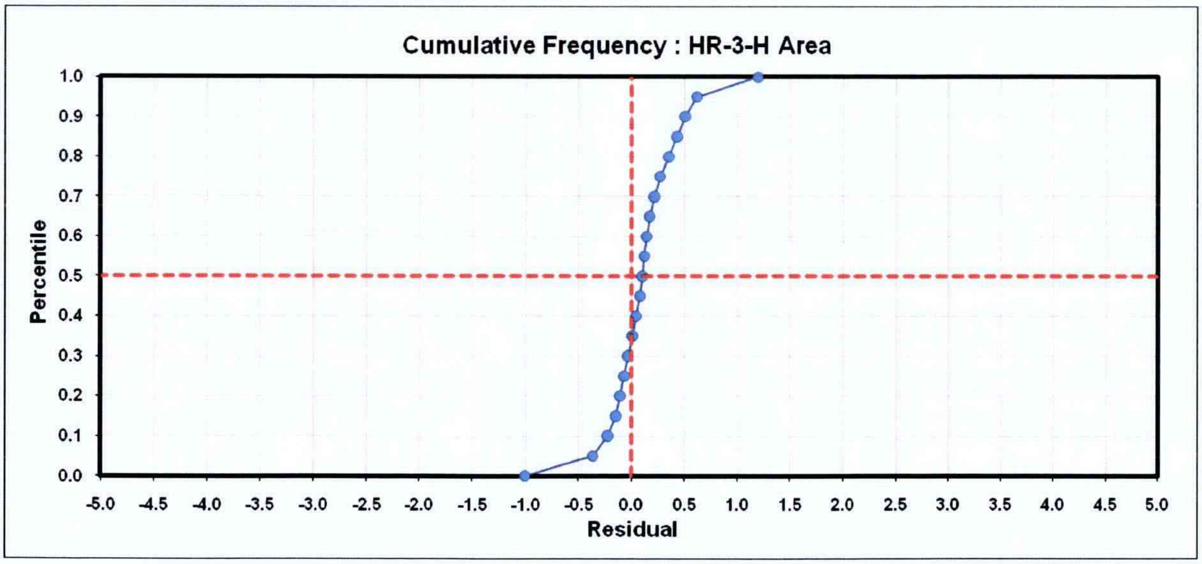

Figure 7-10. Cumulative Frequency of the Water Level Residuals in 100-H: Model Validation.

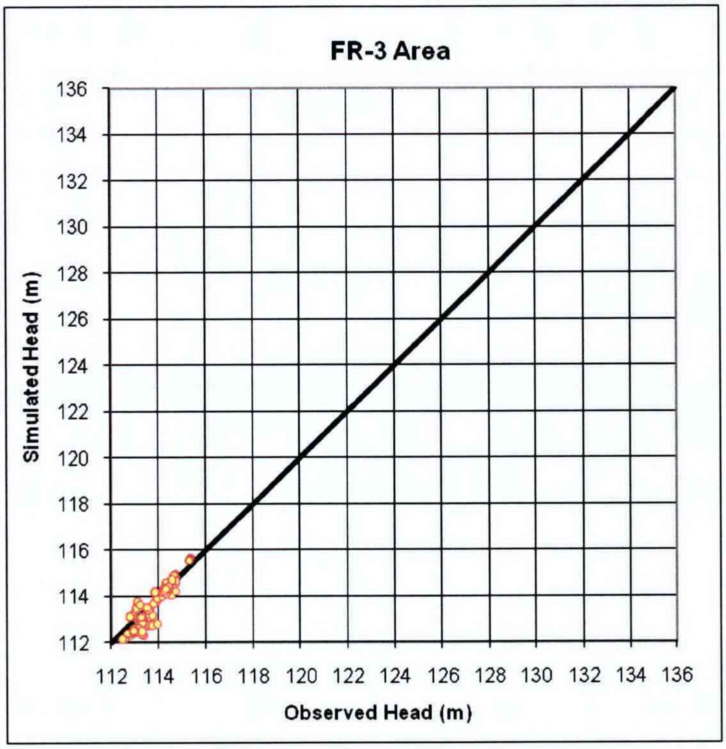

Figure 7-11. Measured versus Calculated Water Levels in 100-F: Model Validation.

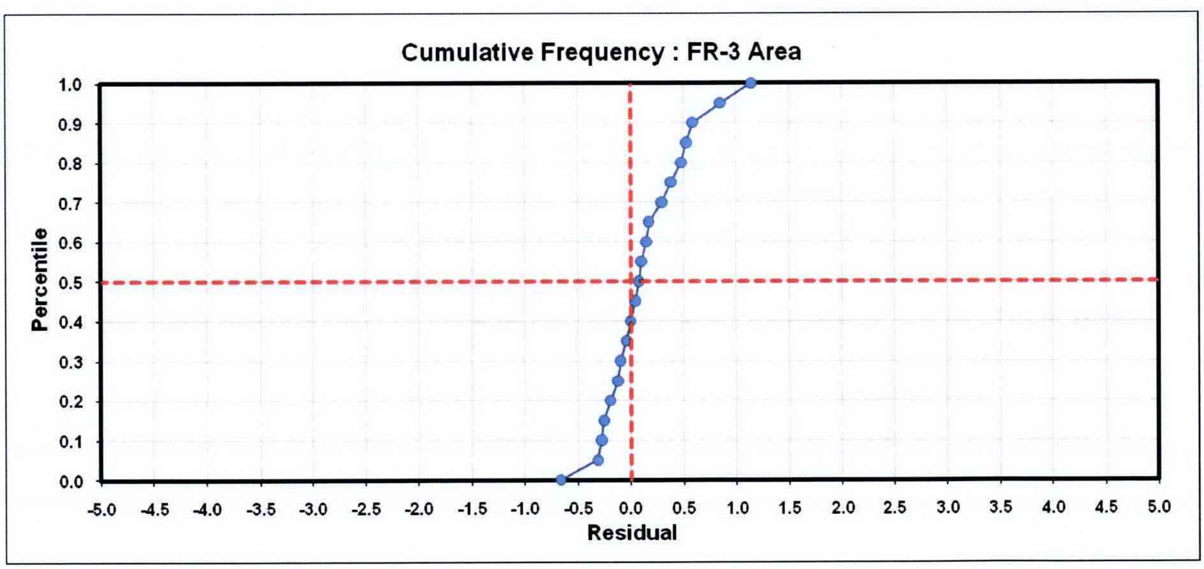

Figure 7-12. Cumulative Frequency of the Water Level Residuals in 100-F: Model Validation.

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8 Contaminant Transport Modeling

This section describes the contaminant transport features that can be simulated using the current version of the 100AGWM, and the general procedures used to assign parameter values describing transport characteristics for contaminants of concern in the 100 Areas. Detailed, application-specific, explanations of contaminant transport properties (parameters) and simulations will be provided in application-specific Environmental Calculation Briefs (ECFs) when the 100AGWM is employed. Steady-state and/or transient transport simulations are based upon the groundwater flow fields calculated by the groundwater flow component of the 100AGWM. Simulation of the transport of contaminants is accomplished using a version of the multi-species reactive transport simulator MT3DMS, modified specifically for use at the Hanford Site.

The 100AGWM was originally developed to simulate groundwater flow and the advective, non-dispersive, non-reactive movement of water and contaminants in order to estimate the likely extent of hydraulic containment and ultimately capture developed by groundwater pump-and-treat remedies. As the development of remedy alternatives progressed, however, it became necessary to simulate the fate of contaminants – commencing with hexavalent chromium, and later incorporating all contaminants of concern – using mass conservative methods. These capabilities were required in order to enable simulations of:

- Concentrations over time at point locations (for example, corresponding to wells) and integrated over broad areas (for example, plumes), and other quantities such as plume masses and volumes, over time.
- Influent concentrations at pumped wells.
- Mixing (i.e., "blended" or combined influent) and treatment of the contaminants by existing and/or proposed above-ground treatment systems.
- Transformations and reactions that some contaminants undergo in-situ, either under natural or anthropogenic conditions – for example, to evaluate the likely impact and effectiveness of in-situ bio-degradation as a remedy component.

Although the subsurface migration of most contaminants at the Hanford site is dominated by advection - that is, the movement of dissolved contaminants in the subsurface with, and in the general direction of, groundwater flow - contaminants do undergo processes of dispersion, adsorption-desorption, transformations – such as radioactive decay – and rate-limited degradation in the presence of suitable catalysts. Indeed, studies by PNNL (PNNL-17674, *Geochemical Characterization of Chromate Contamination in the 100 Area Vadose Zone at the Hanford Site*) suggest that although advection is the primary transport mechanism, contaminant transport cannot be adequately simulated with advection alone since advection only effectively simulates the highly mobile mass that is already dissolved in the actively moving groundwater. Contaminants undergo reactions, and contaminant mass can also be held in heterogeneous parts of the aquifer of low hydraulic conductivity or disconnected pore spaces. This immobile mass constitutes a continuing source of contaminants to the mobile domain, facilitated by mass transfer between these mobile and immobile domains.

Based on these observations, and on previous simulations conducted at Hanford, the following features of the transport of contaminants in the 100 Areas were considered in simulations using the 100AGWM:

- Advection. For the majority of simulations, this is represented using the implicit finite-difference technique, for computational expediency. Advection is not discussed further in this report.
- Dispersion. The contribution of mechanical dispersion and molecular diffusion to the migration of contaminants was not simulated because simulations including dispersion generally result in spreading and lower predicted concentrations than simulations excluding dispersion, which can lead to overly-optimistic projections of cleanup times and natural attenuation. Dispersion (and diffusion) are not discussed further in this report.
- Radioactive decay. Where applicable, this is simulated using appropriate half-lives for radionuclides. Half-lives used in specific applications will be listed in the corresponding application-specific ECF(s).
- Reversible sorption. Where applicable, this is simulated using a linear isotherm (i.e., instantaneously reversible (de-)sorption using a distribution coefficient: K_d). Distribution coefficients (K_ds) used in specific applications will be listed in the corresponding application-specific ECF(s). However, some important considerations for the selection of appropriate K_d values in transport simulations are given in the subsections that follow.
- Dual-domain (dual-porosity) transport. This is detailed further below in subsection 8.1.
- (Bio-)Degradation under natural and artificially augmented (mediated) conditions. This is detailed further below in subsection 8.2.
- Treatment system processes. This includes the blending, treatment, and/or recirculation of dissolved contaminants that are extracted by pumped wells and returned to the aquifer via injection wells. This is detailed further below in subsection 8.3.

The subsections that follow detail the implementation of dual-domain (dual-porosity) transport; bio-degradation; and treatment system processes in transport simulations using the 100AGWM. A final subsection describes how initial conditions are typically developed for transport simulations using the 100AGWM. It is important to note that the following discussions describe the methodology of implementation of certain contaminant transport processes using MT3DMS as the transport simulator for the 100AGWM: the application-specific parameterization of these transport processes will be described in application-specific environmental calculation briefs, and will depend on the contaminant(s) simulated and other features of the specific application.

8.1 Dual-Domain Transport

Consistent with studies by PNNL (PNNL-17674), which suggest that contaminant mass can reside in, and slowly be released from, low hydraulic conductivity regions of the heterogeneous aquifer and/or disconnected pore spaces – and that this mass can continue to contaminate the moving groundwater - the 100AGWM simulates the migration of contaminants using the dual-domain (or dual-porosity) approach that effectively divides the aquifer into two domains with contrasting transport characteristics.

Using the dual domain simulation approach, it is assumed that contaminant migration – dominated by advective-dispersive transport – occurs predominantly in the mobile domain while mass can transfer between the mobile and immobile domain. In simulations completed using the 100AGWM mass transfer was simulated as a linear function of the dissolved concentration gradient between the two domains. Figure 8-1 schematically depicts the dual domain processes that the 100AGWM simulates. Note that it is assumed that sorption occurs only within the immobile domain so that the partitioning coefficient Kd in the mobile domain is zero.

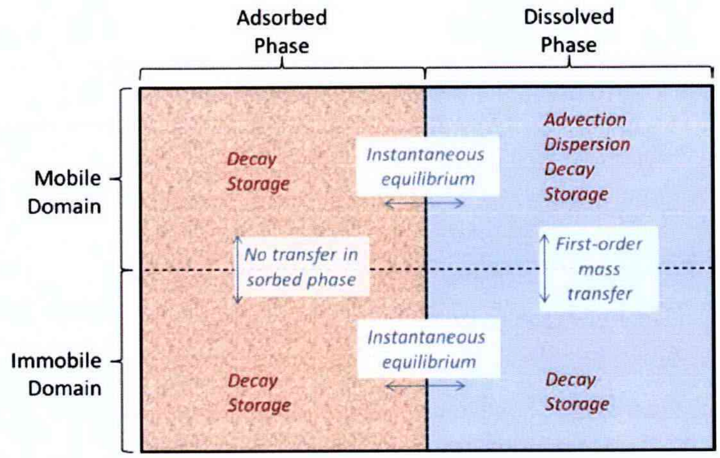

Figure 8-1. Conceptual representation of dual-domain (dual-porosity) simulation (*Blue font represents mass transfer between various phases/domains; red font represents simulated transport processes*).

To develop initial parameters for the MT3DMS dual-domain formulation, benchmark calculations evaluating migration in a soil under single- and dual-domain conditions were performed using MPNE1D (*MPNE1D, Analytical Solution for One-Dimensional Solute Transport with Multiprocess Nonequilibrium* [Neville 2004]). The analytical solution describes the following transport processes: advection; dispersion; dual-porosity; mobile-immobile mass transfer; combined equilibrium and kinetic sorption; and first-order transformation reactions. The following are the principal assumptions that underlie the use of the MPNE1D code to develop initial parameters for the MT3DMS dual-domain formulation with the 100AGWM:

- The domain is represented as a dual porosity continuum, with mass movement between the mobile and immobile domains modeled as first-order mass transfer.
- Sorption occurs at equilibrium and/or rate-limited sites.
- Transformation reactions are modeled as first-order decay processes.
- The material properties are spatially uniform and temporally constant.
- The Darcy flux is steady, one-dimensional, and spatially uniform.
- Longitudinal dispersion (when simulated) is assumed to be a Fickian process, characterized by a constant dispersion coefficient.
- The initial concentrations in each domain are specified and assumed in equilibrium.

The conceptual model developed to evaluate appropriate parameters for the 100 Areas dual-domain simulations consisted of a one-dimensional soil column of 50 cm (19.7 in.) in length. Uniform hydraulic and transport parameters are assumed throughout the soil column. A steady-state flow field is assumed with a Darcy flux of 1.319 cm/day (0.519 in./day) under confined conditions. Contaminant transport is simulated for a period of 40 days for a conservative solute with no dispersion or decay. The initial concentration in the soil column is assumed equal to zero. The boundary condition at the top of the soil column represents a contaminant flux of 1 g/cc from the start of simulation to 17.6 days. From 17.6 days to 40 days, the influx of mass drops to zero and no additional mass is introduced into the system. Breakthrough curves are calculated at a distance of 30 cm (11.8 in.) from the top of the soil column. The parameters used in the problem are shown in Table 8-1. Numerical simulation of the conditions described in the conceptual model using the same parameter values were performed using MT3DMS, and the results were compared to the analytical solution.

Table 8-1. Parameter Values for the Simulation of Plume Migration in a Soil Column.

Parameter	Value
Bulk density, ρb (g/cm^3)	1.72
Mobile water content, θm (cm^3/cm^3)	0.18
Immobile water content, θim (cm^3/cm^3)	0.045
Total water content, θ (cm^3/cm^3)	0.225
Fraction of mobile water content, f (-)	0.8
Darcy flux, q (cm/day)	1.319
Soil-water distribution coefficient, Kd (cm^3/g)	0.3

A single-domain model that simulates the movement of a conservative plume through a soil column was developed first to understand the effect of each individual process that influences the movement of contaminants under dual-domain conditions. Figure 8-2 shows breakthrough curves for a single-domain simulation using the analytical solution and the numerical model, assuming a mobile porosity of 18 percent and no consideration of the immobile domain or adsorption. The breakthrough curves suggest excellent agreement between the analytical and numerical solutions.

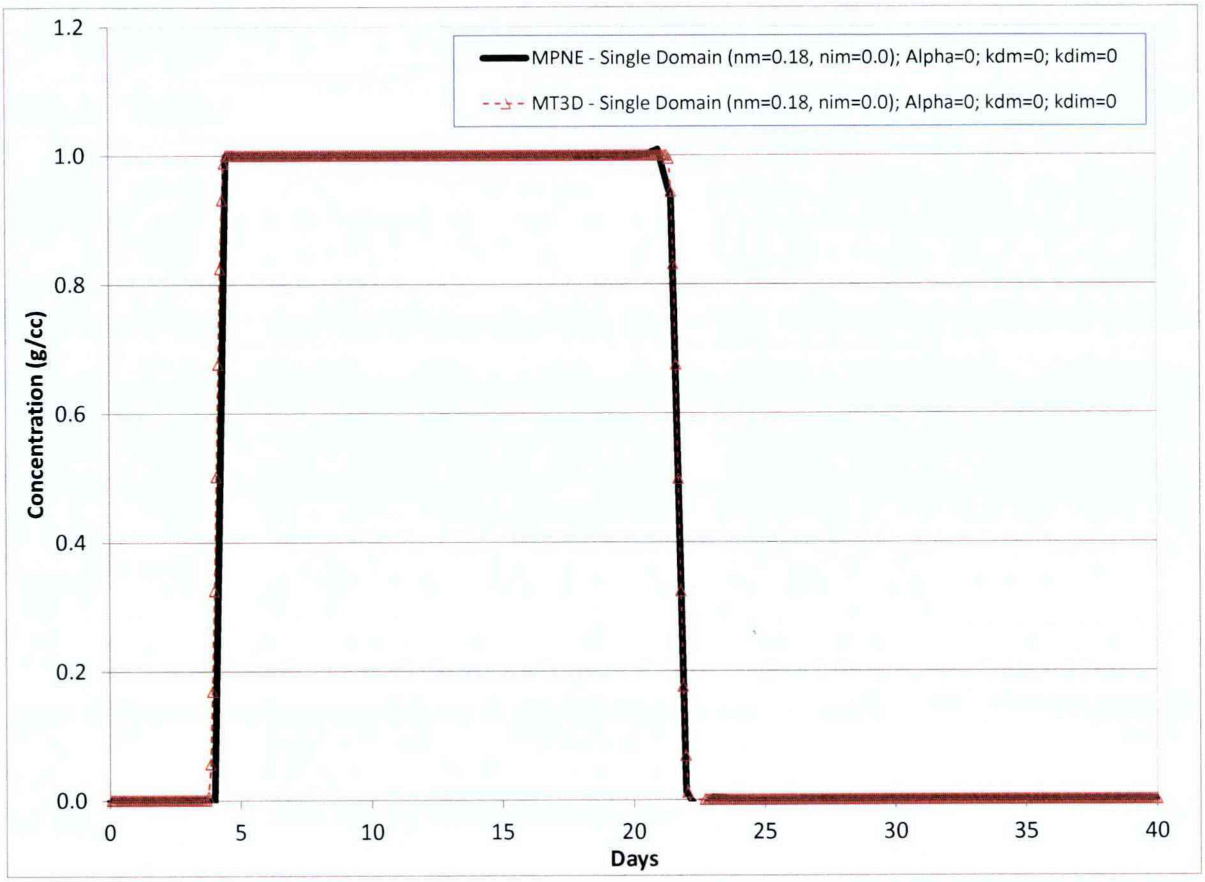

Figure 8-2. Breakthrough Curves – Single Domain

Dual-domain simulations were then performed assuming 20 percent immobile water fraction, which results in an immobile water content of 4.5 percent and mobile water content of 18 percent, for a total water content of 22.5 percent. Adsorption was also simulated in the form of instantaneous linear adsorption in the immobile domain. A value of 0.3 cc/g, was used for the Kd. Two cases were examined, for different values of the first-order mass transfer coefficient α: (1) α equal to zero, reducing the system to a single domain; and (2) α equal to 0.01, representing a dual-domain system.

When the mass transfer coefficient α is set to 0.01, solute mass is able to enter and leave the immobile domain generating a characteristic "tailing" of the contaminant plume migration. When compared to the single-domain simulation, lower solute concentrations are initially observed in the mobile phase. This can be attributed to mass transfer from the mobile domain into the immobile domain when the immobile dissolved concentration is lower than the mobile domain concentration. Subsequently, mass in the immobile domain is slowly released into the mobile domain as the mobile domain concentrations decrease.

Figures 8-3 and 8-4 show the breakthrough curves obtained by the analytical solution and the numerical model, respectively. The breakthrough curves indicate additional retardation of the plume migration due to adsorption.

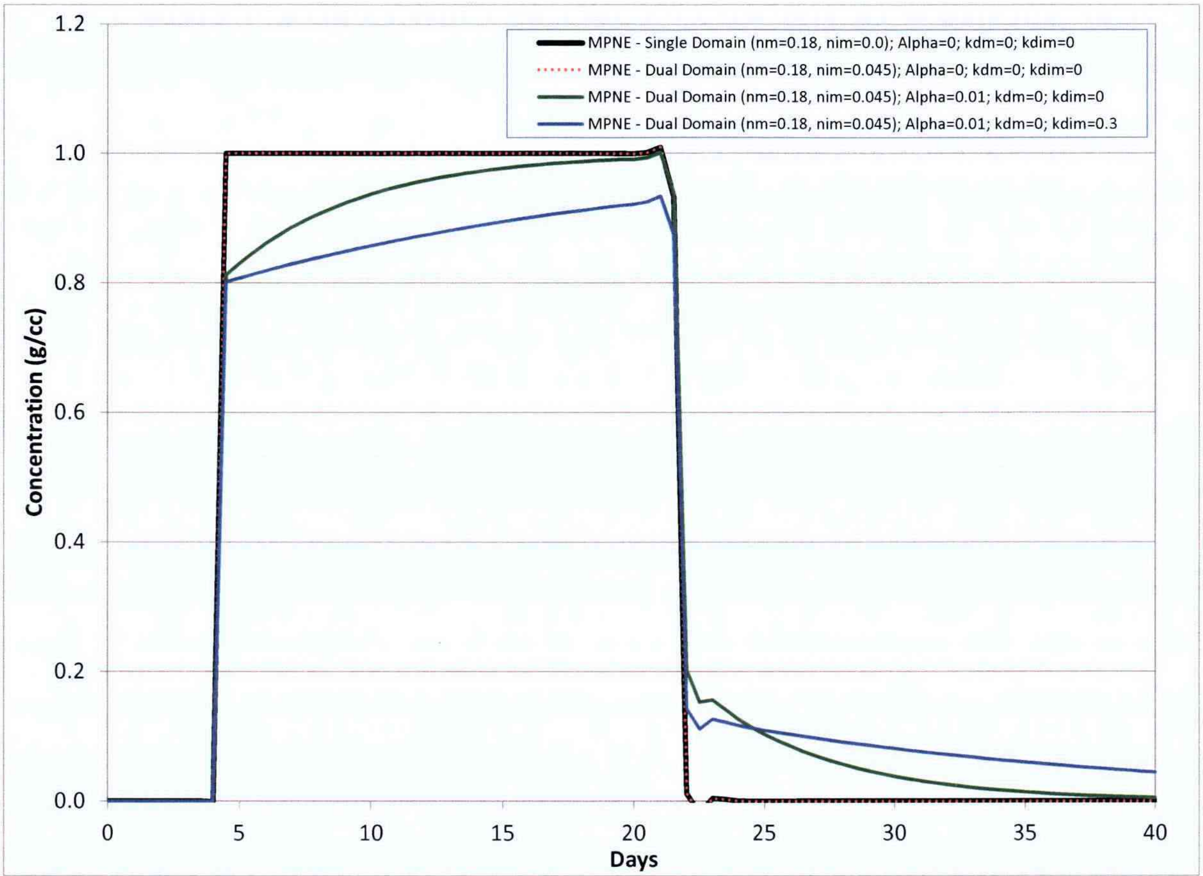

Figure 8-3. Breakthrough Curves – Dual Domain, Analytical Solution

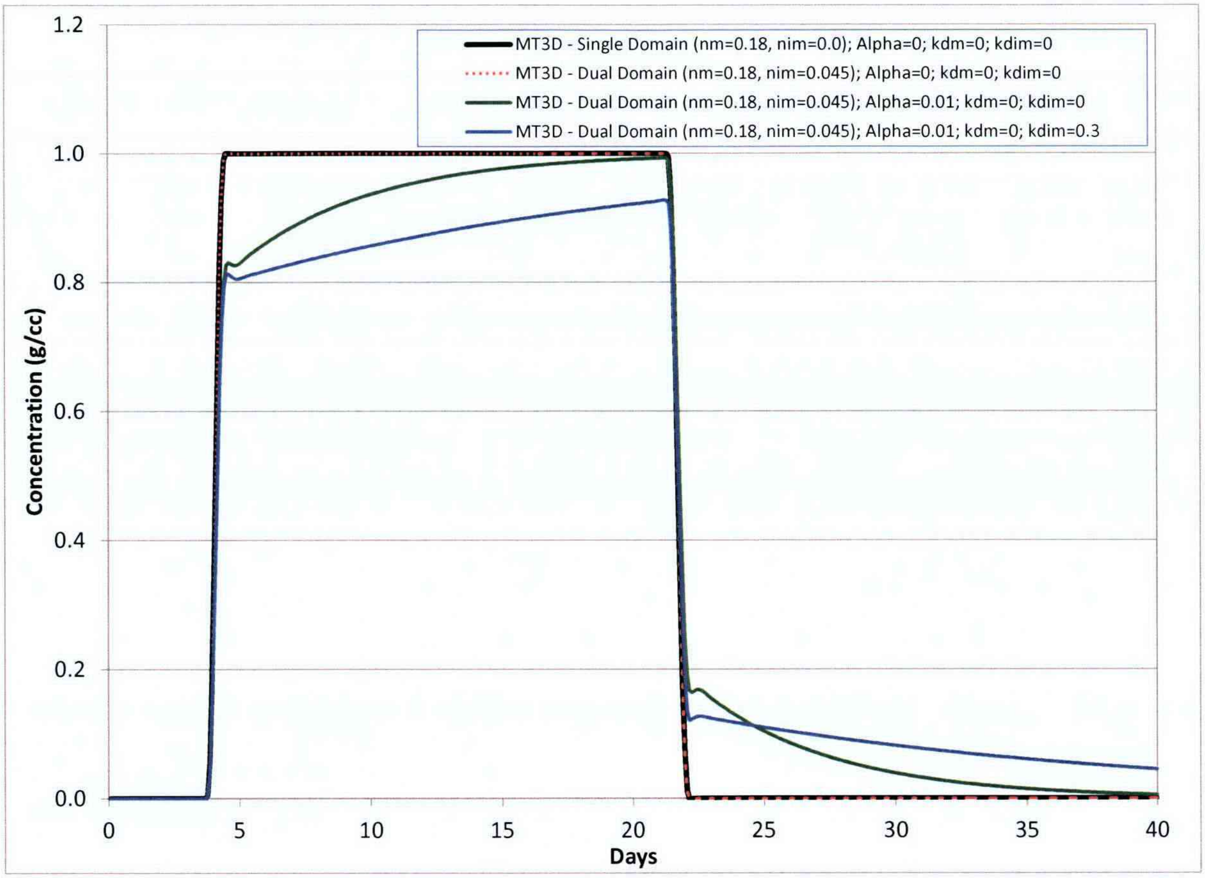

Figure 8-4. Breakthrough Curves – Dual Domain, Numerical Simulation

Table 8-2 shows the solute mass introduced to, recovered from, and remaining in the system at the end of the simulation timeframe under single-domain conditions, dual-domain conditions, and dual-domain conditions with absorption considered. Although the entire solute mass was flushed out of the system within the 40-day simulation period, up to 6 percent of the mass introduced into the system remains in the soil column under dual-domain conditions including adsorption.

Table 8-2. Mass Balance of Solute for Each Scenario After 40 Days.

Scenario	Total In (g)	Mass Remaining (g)	Total Out (g)
Base case, single domain	23.264	0.000	23.264
Dual domain, no sorption	23.264	0.118	23.147
Dual domain, sorption in immobile phase	23.264	1.395	21.870

The results of the simulations undertaken using MPNE1D to benchmark the dual-domain implementation within MT3DMS for th100AGWM simulations indicates, much as expected, that small-scale heterogeneities in the aquifer could result in the sequestering and slow release of significant amounts of contaminant mass - thereby, prolonging the necessary time to achieve aquifer cleanup. The parameterization of the dual domain system described above – i.e., a total porosity of 22.5%, comprising a mobile porosity of 80% (0.18) of the total porosity, and an immobile porosity of 20% (0.045) of the total porosity, with a rate-transfer coefficient of 0.01 between the two domains – was retained for the simulation of all contaminants of concern using the 100AGWM.

Using this general apportionment of the mobile and immobile domains, contaminant-specific parameters for the distribution coefficient (K_d) within the immobile domain are required. These are described within each application-specific calculation brief, together with supporting information. Nonetheless, it is expected that the dual domain parameterization may vary depending on the simulated contaminant and the objective of the simulation. For example, the distribution coefficient of 0.3 g/cc described above has been used for simulations of CrVI using the 100AGWM. Some recent work, described in the calculation brief "Evaluation of Hexavalent Chromium Leach Test Data Conducted on Vadose Zone Sediment Samples from the 100-Area" (ECF-HANFORD-11-0165 Rev. 0) suggests that a higher-valued distribution coefficient (K_d) of 0.8 may be appropriate as a conservative lower limit when representing residual hexavalent chromium that is present in fine sediment after several pore-volume flushes of contaminated sediments have occurred (ECF-Hanford-11-0165). Future revisions of the groundwater fate and transport models will consider this new information in parameterizing the dual-domain representation of the transport of CrVI and other contaminants in the 100AGWM. Model parameters will also be calibrated to match observed conditions and information on the movement of CrVI plumes across the River Corridor as these data become available.

8.2 Bio-remediation

The majority of flow-and-transport simulations conducted using the 100AGWM to-date focus on the fate of groundwater and contaminants under "ambient" and under remediation conditions, with the principal groundwater remedy typically groundwater pump-and-treat. However, the 100AGWM has also been used to evaluate the efficacy of in-situ bioremediation either as an augmentation to groundwater pump-and-treat remedies, or as a stand-alone remedial alternative. To accomplish this, the 100AGWM has been used to make predictive simulations of the impact of injectiong water amended with a suitable substrate for remediation of one (or potentially more) target contaminants. The discussion in this subsection provides the general approach to completing these bio-remediation simulations: the case of the bio-remediation of CrVI using a source of carbon as the substrate is used as an example to illustrate details of the implementation.

To date, the 100AGWM has been used to simulate the bio-remediation of a single contaminant, using a single injected species (substrate). That is, simulations consider the transport and interaction of 2 species - the first species being the contaminant of concern, and the second species being the injected substrate. The substrate injection is simulated as an injection concentration that enters the groundwater system through an injection well using the Source Sink Mixing (SSM) package of MT3DMS. An instantaneous reaction is simulated, with a specified stoichiometry – i.e., a specified ratio of the substrate that is required to reduce / consume / transform the contaminant of concern such that under most conditions absent transport of the species either (a) the substrate completely and instantaneously reduces / consumes /transforms the contaminant in the model cell or (b) the substrate is entirely consumed and reduces / consumes / transforms the corresponding amount of contaminant. This reaction between the two species assumes instantaneous and complete mixing within each model cell, and is represented explicitly in the model. The rate of the reaction - i.e. the amount of contaminant that is reduced / consumed / transformed by the injected substrate - is calculated directly based on the specific reaction stoichiometry for the two corresponding species.

The foregoing approach to simulating degradation can in theory be used to represent direct reduction (or oxidation) and / or bio-degradation / bio-transformation. The approach does not explicitly consider the growth of organisms in the case of bio-remediation: the reaction stoichiometry will in many cases be semi-empirical, based in part upon equations that describe the oxidation-reduction system including the target contaminant, but also considering field experience with similar remediation technologies.

By way of example, if ethanol (C_2H_6O) is used as a carbon source to reduce hexavalent chromium, Cr(VI), to trivalent chromium, Cr(III), the following equation describes the chemical reaction that is involved in the bio-remediation process:

$$C_2H_6O + 4CrO_4^{2-} + 8H^+ \rightarrow 2CO_2 + 4Cr(OH)_3 + H_2O$$

This equation assumes that chromium is present at the Hanford site in the hexavalent form. Using this equation, stoichiometric calculations suggest that every gram of ethanol reduces 4.5 grams of Cr(VI). If however chromium is present in the form of CrO_4^{2-}, then 10.07 grams of CrO_4^{2-} are reduced per gram ethanol oxidized., As written, this equation does not consider the demand that is placed on the ethanol from other electron acceptors residing in the aquifer. In reality, before the substrate reacts with the chromium, it is consumed by two processes:

1. Bio-activity of the microbes that diminishes the substrate concentration; and,
2. Competitive reaction with other compounds present in the system.

Since neither bioactivity of microbes nor the reaction of the substrate with secondary compounds is explicitly simulated in the 100AGWM, the MT3DMS reactive transport simulator developed for use with the 100AGWM enables a first-order decay term to be applied to the substrate that can approximate the consumption of the substrate over time due to these two processes. Typically, the half-life of this first-order decay term will be empirically based, derived from field observations of pilot scale studies and other field-scale applications. In the case of CrVI reduction to CrIII though injection of ethanol, a first-order decay rate for the substrate is provided that assumes that the substrate has a half-life of 20 days as a result of competing demands. In this context, "half-life" refers to the surrogate representation of the consumption of the substrate by a variety of processes that are collectively represented as a first-order decay process.

As for the dual-domain simulations, the specific parameters used to describe a bio-remediation scenario will be described in the corresponding application-specific environmental calculation brief.

8.3 Radio-active Decay

Decay of radionuclide contaminants is simulated as a first-order decay process, consistent with the physics of the decay process. Although radioactive decay is often described in terms of a "half-life" (i.e., $t_{½}$) – equating to the time required for the activity to decline to half of its initial value – MT3DMS provides the capability for simulating first-order decay by specifying a decay rate, λ, calculated as follows:

$$t_{½} = \frac{}{}$$

$$= \frac{}{}$$

As for the dual-domain simulations, the specific parameters used to describe radioactive decay will be described in the corresponding application-specific environmental calculation brief.

8.4 Pump and Treat System Circulation

When groundwater is extracted for above-ground treatment, the treatment technology is generally selected to be effective in removing (by one process or another) one or more targeted contaminants of concern. Certain technologies are very effective for certain COCs – potentially removing all of the contaminant from the water; whereas, certain technologies may not completely remove a COC but may remove sufficient of the COC that the treatment effluent meets discharge requirements. Finally, some contaminants are very difficult, or technically impracticable, to remove from pumped groundwater. An example of the latter is tritium, which is an isotope of hydrogen and as such when combined with oxygen has essentially the same properties as water.

In order to represent the effect of above-ground treatment systems on the quality of extracted (and re-injected) groundwater, the MODFLOW and MT3DMS simulators that are used to execute the 100AGWM are able to simulate the circulation and treatment of extracted COCs within a pump and treat system comprising a network of extraction and injection wells. While the primary COCs are actively treated – to a level (efficiency, or effectiveness) that is specified by the user - secondary contaminants simply pass untreated from the extraction wells, through the notional treatment system, and are returned to the groundwater domain via injection wells. Blending of the extracted water can occur – as occurs within above-ground treatment systems – which will alter blended concentration so that the effluent concentration is generally lower (more dilute) than the highest influent concentration for untreated contaminants. This movement of contaminants through a pump-and-treat system is simulated using the Contaminant Treatment System (CTS) package implemented in MT3DMS (Bedekar et al, 2011).

8.5 Development of Initial Plumes for Transport Simulations

To complete a predictive (forward-in-time) simulation of the fate of contaminants that are currently presenting in groundwater, a depiction of the current extent and concentration of each contaminant of concern is required. This is referred to as the contaminant transport "initial condition", or the "initial plume". This initial plume is a depiction of the spatially-varying concentration of a contaminant of concern, typically prepared on the basis of measured concentration data obtained by sampling wells. Initial plumes can represent these concentrations in two-dimensions (2D) or three-dimensions (3D), depending on the availability and location of the sample data, and the discretization of the numerical model.

Prior to the time of publishing Revision 2 (Rev 2) of this report, contaminant fate-and-transport simulations conducted using the 100AGWM focused on evaluating the efficacy of alternate groundwater remedies, inconsideration of the current extent of several contaminants of concern. This required construction of initial plumes for each of those contaminants. Although the availability (in both space and time) of sample results for each COC often varies, the following systematic approach was taken to the preparation of initial plumes for the 100AGWM simulations to-date:

1. The decision was made to interpolate sample data in two-dimensions rather than three-dimensions. Though there is some evidence of vertical variability in concentrations in some locations, this decision was based upon:

    (a) The relative proportions (extents) of contamination in two dimensions (i.e., aerial extents) versus the vertical extents. In most places throughout the 100AGWM, individual groundwater plumes have aerial extents on the order of hundreds to thousands of meters, whereas the saturated thickness of the unconfined aquifer is in most places less than about 10 to 15 meters, with the exception of some areas of 100-K and 100-BC.

(b) The inconsistency of vertical trends in concentrations at different locations: in some locations and for some COCs, the concentration decreases with depth, while at other locations and for other COCs the concentration increases with depth.

(c) Projection of three-dimensional contaminant concentration data on to a two-dimensional depiction typically "exaggerates" the likely aerial extent at each vertical interval within the aquifer, such that a remedy designed to contain and recover (or treat in-situ) the contamination throughout the aquifer thickness will more likely be "over-designed" than "under-designed", which is the more appropriate outcome for a Feasibility-Study-level assessment.

2. Groundwater sample data available from wells and aquifer tubes over the last two years were collated and tabulated.

3. These data were summarized in to a table of the maximum sampled concentration, for each contaminant of concern, at each easting-northing location (i.e., typically, corresponding with each well location, but at nested wells this would correspond with the maximum concentration within *any* of the nested wells / screens). This provides a data set that comprises the maximum sampled concentration over two years, "compressed" in to two dimensions.

4. Interpolation of this "2D-maxmimum" point data set to a continuous grid using quantile kriging, a variant of ordinary kriging in which the quantile (rank-score) transform of the data is interpolated, and back-transformed in to the original data units.

5. Review and adjustment by one or more OU technical leads of the interpolated contours obtained via quantile kriging, providing qualitative input in areas where independent information exists (such as areas of previous clean-water injection, or areas of excavation, etc.).

The resulting two-dimensional continuous concentration distribution for each COC was then interpolated on the 100AGWM using the nearest-neighbor technique.

Specifics of the interpolation algorithm, input point data sets, and any adjustments made to the data sets or interpolated contours, will be provided in the corresponding application-specific calculation brief.

9 Model Assumptions and Limitations

The principal assumptions and limitations of the modeling effort are described below:

- The Ringold Upper Mud (RUM) Formation, where present, is considered a vertical no-flow boundary. However, sensitivity analysis should be performed to examine the effects, if any, of possible flow across the bottom of the model domain on results obtained using the 100AGWM, including plume migration and the effectiveness of proposed groundwater remedies.
- River-aquifer interaction and river stage variation in particular represent the most important mechanism for water level changes near the shoreline and at some distance inland. The accuracy of the river gauge data is therefore essential for the correct representation of the river stage temporal variation in the model and the calculation of water levels during the modeling timeframe. Missing or incorrect river gauge data can lead to misrepresented river stage variations.
- Three-dimensional representation of the river bathymetry has not been incorporated in the current version of the 100AGWM due to lack of complete bathymetry data at the time of model development. Therefore, aquifer-river interaction is represented in the model based on an approximate vertical discretization of the river profile given the interpolated river stage and assumed bottom elevation along the Hanford reach. Detailed river bathymetry data has been obtained and is available as of winter 2011, and will be incorporated.
- Fluid flow in the vadose zone above the saturated aquifer (i.e., above the water table) is not simulated.
- With respect to the contaminant transport processes described in this report, small-scale heterogeneity and its effect on contaminant transport are incorporated in the model through a dual-domain formulation. However, the parameters that describe mass transfer between the mobile and immobile phases are calculated based on limited information from soil column experiments. Actual field-scale values could vary significantly and should be evaluated through model calibration when remedy mass recovery data are collected.
- The 100AGWM transport simulations do not include continuing sources in the vadose zone or the RUM. The presence of such sources could significantly prolong aquifer cleanup times for groundwater remedies simulated using the 100AGWM.

As a result of the above - and consistent with recommendations made throughout the development of the 100AGWM in support of remedy design and evaluation - simulated COC distributions in the future are best interpreted as estimates and not as absolute predictions: all important simulation results should be verified using field data where possible. Numerical transport modeling over long timeframes are most appropriately used for comparative remedy analysis – i.e., to identify the likely benefits of one remedy versus another - through qualitative assessments of long-term plume migration patterns, rather than to accurately calculate point concentration time-series at future times.

Monitoring data should continue to be compiled and analyzed to further improve estimation of the parameters associated with the simulations undertaken using the 100AGWM, and the model should be updated accordingly to provide improved predictions over time.

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10 Model Configuration Management

The model described in this report is uniquely designated as the 100 Areas Groundwater Model Version 3. For purposes of archival in EMMA, model version and simulation run numbers are assigned to the model to enable complete identification and traceability based on the guidelines of the Quality Assurance Project Plan for Modeling (QAPjP) (CHPRC-00189, *CH2M Hill Plateau Remediation Company Environmental Quality Assurance Program Plan*). Based on these guidelines, the convention for naming model versions and designating simulations includes six entries in the form:

Model Name, Version (N1), Simulation G(N2)_B(N3)_I(N4)_TC.CC_CN_iter

where:

Model Name: a descriptive character string to uniquely identify the model.

N1: Major version number (for readily identifiable distinct model).

N2: Model grid; entry is an index number.

N3: Flow boundary conditions; entry is an index number.

N4: Initial conditions; entry is an index number.

F/TC: Flow or Transport code ("p" for particle tracking or "c" for contaminant transport)

CC: Constituent code.

CN: Computer Name.

iter: Iteration; a sequential number to distinguish between multiple runs (note that it is not necessary to save and archive all successive iterations)

Although this is Version 3 of the 100AGW model, it is the first model version to be archived in EMMA. For that purpose and based on the QAPjP naming convention the current version of the model is named:

100Area_Historic_N1_G1_B1_I1_F_00_FE363_3

10.1 Model Version History

Version 1 of the 100AGW model was first developed to evaluate the system performance as part of the 100-KR-4 P&T expansion (DOE/RL-2006-75, *Supplement to the 100-HR-3 and 100-KR-4 Remedial Design Report and Remedial Action Workplan for the Expansion of the 100-KR-4 Pump and Treat System*). This two-dimensional steady-state model was constructed using MODFLOW to simulate flow and MODPATH to simulate particle tracking and evaluate capture zone development and system performance for the expanded P&T system in 100-KR-4. The single model layer represented the unconfined aquifer above the RUM with the hydraulic conductivity distribution reflecting the corresponding formation where the water table lied. The model boundary conditions consisted of river cells representing the Columbia River and GHB cells everywhere else along the perimeter of the active model domain.

Version 2 of the model was developed for the purposes of P&T system RPO in 100-HR-3 and 100-KR-4 which required contaminant transport simulations to develop projections of hexavalent chrome distributions and evaluate plume migration patterns and attainment of river protection and aquifer cleanup goals. For that purpose the groundwater flow model was converted to transient state and coupled with a contaminant transport model using MT3DMS (SGW-46279, *Conceptual Framework and Numerical*

Implementation of the 100 Areas Groundwater Flow and Transport Model, Rev.0). The model grid was further refined in the vicinity of each OU so that transport processes were sufficiently represented in the model. A transient river stage was adopted with monthly stress periods to reflect the water level variations in the aquifer and better reproduce hydraulic gradient reversals during high and low river stage periods. Contaminant transport was considered and a dual-domain approach was introduced to simulate the tailing effects of the hexavalent chrome migration. The model was used to support the calculation of appropriate pumping rates for 100-HR-3 OU injection and extraction wells to achieve RPO objectives by 2012 and 2012 (SGW-40044, *100-HR-3 Remedial Process Optimization Modeling Technical Memorandum*).

The current Version 3 was developed as described in this report to support the RI/FS for each 100 Area OU. The groundwater model was expanded to encompass all 100 Area OUs, simulating (a) groundwater flow as three-dimensional to explicitly represent the Hanford formation and Ringold Unit E Formation that comprise the unconfined aquifer across the 100 Areas; and (b) contaminant transport for various COCs in each OU. This version of the model is implemented using a newer version of MODFLOW-2000 with the inclusion of the ORTHOMIN solver and capabilities to address dry cell problems.

11 Peer Review Panel Recommendations

A technical peer review team was assembled by CHPRC in September 2009 to review the 100 Areas flow and transport model implementation, which at the time simulated the flow and transport in two dimensions. The general purpose of the review was to assess whether the 100 Areas model, as discretized and implemented at the time, with related input parameters and boundary conditions were technically defensible and appropriate for the intended application. Specifically, as defined in the original scope of work, the reviewers were requested to provide an assessment of the following aspects:

- Modeling objectives
- Model code selection
- Modeling application and conceptualization approach
- Input data selection and representation
- Model calibration approach
- Model uncertainty analysis
- Adequacy of model documentation
- Adequacy of quality assurance/quality control protocols.

During the course of the review process, specific topics of concern were discussed with the members of the review team, including the following:

- Whether the 100 Areas model should be relied upon to guide decisions related to river protection and plume remediation relative to Tri-Party Agreement milestones and performance-based initiatives
- Whether the CHPRC modeling needs are being met by the current modeling arrangement.

Tasks performed by the review team were as follows:

- Conducted meetings with the modeling team members
- Reviewed relevant reports and model documentation
- Assessed the adequacy of overall model conceptualization and accuracy of primary model input parameters
- Performed predictive simulations for 100-HR-3 OU, as an example, comparing current assumed transport parameters and transport parameters selected by the review team.

Based on the information obtained during the review and independent sensitivity analyses by the review team, it was the consensus of the review team that the basic approach of developing the 100 Areas model to address questions related to two-dimensional hydraulic capture is technically defensible. The site data that were assimilated during the model development process, the hydrologic processes that are simulated within the modeling framework, and the scale of the modeling analysis were judged by the review team to be reasonable. More complex questions related to three-dimensional hydraulic capture near the edge of the Columbia River and the remediation timeframe could be estimated with the aid of this model as well but, refinements are needed to improve the model's predictive capabilities. Since then, the numerical model was expanded to encompass all 100 Area OUs and it was further discretized vertically to explicitly represent the hydrogeology of the unconfined aquifer in the 100 Areas, using four layers. The review team responses to questions that were raised are provided in Table 11-1.

Table 11-1. Assessment Questions and Review Team Responses

Assessment Question	Review Team Response
Are the modeling objectives clearly defined?	It appears that modeling objectives have evolved over time. Current modeling objectives are not clearly stated in reviewed documents.
Are modeling codes appropriate for current application?	MODFLOW and MT3DMS are commonly accepted analytical tools used worldwide.
Is the modeling approach technically defensible?	The basic approach is acceptable.
Is the distribution of model parameters appropriate?	Hydraulic parameters are acceptable; transport parameters need refinements.
Have models been adequately documented?	Documentation is fragmented and incomplete.
Have models been calibrated?	Hydraulic properties are acceptable; transport parameters need refinements.
How is quality assurance/quality control implemented with model development?	Through applied standard quality assurance/quality control and senior review protocols.
Has an appropriate sensitivity analysis been completed?	In process.

11.1 Recommendations

The review team's recommendations associated with the modeling effort are discussed in this section. Work has been completed or initiated to address a number of the recommendations, including detailing modeling objectives and preparing comprehensive model documentation (i.e., this document), as well as expanding the 100AGWM toward the western boundary to include the 100-BC-5 OU, and to the east to include 100-F/FIU. Table 11.2 lists the review team recommendations and provides information on actions taken to address them and improve the model capability to simulate flow and transport processes in the unconfined aquifer of the 100 Areas.

Table 11-2. Review Team Recommendations and Response Actions

Recommendation	Response Action
Time-series hexavalent chromium concentration data are available for the 100 Areas; such data could be used to help guide the assignment of transport parameter values. Demonstrate consistency between simulated and observed hexavalent chromium trends. Obtain more accurate estimates for the dual-domain parameter values.	Implementation of the expanded P&T in 100-KR-4 and 100-HR-3 will provide sufficient temporal and spatial coverage for the collection of appropriate datasets for such analyses.
Extend two-dimensional analysis to three-dimensional and simultaneously calibrate for both hydraulic and transport targets. Expand the 100 Areas model to improve model predictions and allow for a greater range of "what if" questions to be addressed.	The model grid has been expanded spatially, both horizontally and vertically, to allow for improved representation of the hydrogeology of the unconfined aquifer in the 100 Areas. The revised, three-dimensional model explicitly simulates flow and transport processes in the Hanford formation and Ringold Unit E Formation using four layers.
Expand the western model boundary further to the west	The model grid has been expanded to encompass all

and away from the 100-K Area pumping center to minimize potential boundary condition effects.	100 Area OUs and extend to sufficient distance from all OUs, to prevent any boundary condition effects.
Prepare comprehensive model documentation, including the conceptual framework, translation of the conceptual model into the numerical model, and model calibration.	A comprehensive model documentation report was first published in 2010 and it was revised in 2011. This report constitutes Revision 2 of the modeling report and it documents in greater detail all aspects of the conceptual framework and numerical implementation of the 100 Area model.
Review results from the uncertainty analysis that is currently in progress with the 100 Areas model to identify additional sources and types of uncertainty.	The uncertainty analysis commenced during the Remedial Process Optimization (RPO) process conducted in CY2008/2009. Due to the revisions and expansion of the model structure, and deployment for the River Corridor RI/FS process, the uncertainty analysis has been postponed until the model expansion and RI/FS simulations have been completed.

In addition, the review team provided recommendations regarding additional actions that should be taken:

- Gain consensus among project stakeholders and clearly define modeling objectives.
- Stress to stakeholders the uncertainty in the model predictions. Such uncertainty should be kept in mind when establishing the approach for assessing compliance with Tri-Party Agreement milestones and performance-based incentives, and the potential consequence of not achieving them.
- Modify the performance criteria associated with the river protection Tri-Party Agreement milestones and performance-based incentives so compliance is based on remedy-in-place and evidence of hydraulic performance, as opposed to strict concentration-based criteria.
- Provide additional resources (e.g., modelers) as needed to accomplish recommendations and future modification to the model.

These recommendations should be discussed in relation to recent efforts to develop appropriate remedial strategies within the RI/FS framework for the various COCs and for the implementation of available technologies. Such discussion is outside the scope of this report.

Recommendations for future development of the 100AGW Model beyond Version 3 that are proposed to CHPRC and are currently under consideration include:

- Incorporate river bathymetry to develop river cell discretization and stage/bottom elevations that better represent the spatially varying river-aquifer interaction.
    - Difficulty: Low
    - Priority: High
- Refine the hydrogeologic characterization to address basalt saddle interpretations and uncertainty associated with the development of representative flow boundary conditions inland of the 100-BC-5 OU and along the Gable Gap.
    - Difficulty: Low
    - Priority: High
-

- Update hydrogeologic representation to accommodate recent information acquire during installation of the HX pump and treat system.
    - Difficulty: Low
    - Priority: High
- Update calibration data to include 2011 data and to add wells with newly identified screen information.
    - Difficulty: Low
    - Priority: High
- Sensitivity analysis for all model parameters prior to automated model calibration.
    - Difficulty: Moderate
    - Priority: High
- Incorporate the results of the analysis of recent slug tests as well as well development data in 100-HR-3 to refine the model hydraulic conductivity distribution.
    - Difficulty: Moderate to High
    - Priority: Moderate

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